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Review

Spatial and Temporal Variability of the Impacts of Pinyon and Juniper Reduction on Hydrologic and Erosion Processes Across Climatic Gradients in the Western US: A Regional Synthesis

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Abstract: Pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands are an important vegetation type in the Great Basin, Colorado Plateau, and southwestern desert regions of the western US that is undergoing substantial changes associated with land management, altered disturbance regimes, and climate change. We synthesized literature on the ecohydrologic impacts of pinyon and juniper tree reductions across plot to watershed scales, short- and long-term periods, and regional climatic gradients. We found that the initial plot- to hillslope-scale ecohydrologic and erosion impacts of tree reduction on pinyon and juniper woodlands by fire, mechanical tree removal, or drought depend largely on: (1) the degree to which these perturbations alter vegetation and ground cover structure, (2) initial conditions, and (3) inherent site attributes. Fire commonly imparts an initial increased risk for hillslope runoff and erosion that degrades over time with vegetation and ground cover recovery whereas tree reductions by mechanical means pose fewer initial negative ecohydrologic impacts. Tree reduction by either approach can enhance understory vegetation and improve site-level ecohydrologic function over time, particularly on sites with an initially favorable cover of native herbaceous vegetation and a cool-season precipitation regime. Understory vegetation and ground cover enhancements appear to increase ecohydrologic resilience of some woodland communities to disturbances such as drought, fire, and insect infestations. In contrast, intensive land use, prolonged drought or repeated burning associated with invasions of fire-prone grasses can propagate long-term site degradation through persistent elevated runoff and erosion rates. Our synthesis suggests the annual precipitation requirement for increases in plot- to hillslope-scale soil water availability for herbaceous enhancement through tree removal likely ranges from 200–400 mm for sites in the Great Basin and northern Colorado Plateau (cool-season precipitation regimes), and, although suggested with great uncertainty, likely exceeds 400 mm for woodlands with rain-dominated precipitation regimes in the southwestern US. Overall, literature is inconclusive regarding tree reduction impacts on watershed-scale changes in groundwater and streamflow. To date, there is little evidence that drought-related changes to vegetation in pinyon and juniper woodlands substantially affect watershed-scale water availability and streamflow at the annual time scale. Our synthesis identifies key knowledge gaps to overcome in improving understanding of the ecohydrologic and erosion impacts of broadly occurring pinyon and juniper tree reductions in the western US.

Keywords: climate change; cutting; die-off; drought; ecohydrology; evapotranspiration; fire; groundwater; hydrologic connectivity; interception; pattern-process; rangelands; recharge; runoff;

soil water; structure-function; tree mortality; tree removal; water yield; woodlands; woody plant encroachment

1. Introduction

Pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands (hereafter PJ woodlands) are an ecologically important vegetation type throughout the western US owing to their broad distribution, dynamic ecological impacts, and provision of an array of ecosystem services [1–4]. Pinyon and juniper conifers now exist on over 400,000 km^2 of the western US and their distribution is increasing [3,4]. PJ woodlands are commonly found at elevations ranging from several hundreds of meters to >2000 m above mean sea level throughout the Great Basin, Colorado Plateau, and the southwestern US, inclusive of the mountainous regions in the Sonoran and Chihuahuan Deserts in Arizona and New Mexico (Figure 1) [1,4–7]. These woodlands now occupy approximately 190,000 km^2 across this broad area, a 10-fold increase since the mid to late 1800s [1,2,8–10]. Recent syntheses indicate about 90% of the current PJ domain was previously occupied by sagebrush (*Artemisia* spp.) vegetation, most of that in the Great Basin and Colorado Plateau (see [9,10]). Substantial tree infilling has occurred on PJ woodlands throughout the western US in the past 150+ years [1–4]. Attribution of causal factors for range expansion and infill of PJ woodlands is somewhat controversial by region, but there is general agreement regarding a combination of causal factors for west-wide expansion and infill, including overgrazing, an associated decrease in fire frequency, climate variability, and increased atmospheric CO_2 [1–3,6,8,11,12]. Although PJ woodland expanse has increased across much of the western US, recent extensive PJ woodland die-offs have also occurred due to drought and insect infestations [13–23]. Pinyon and juniper provide a host of important ecosystem services; however, woodland range expansion and infill also pose ecological ramifications to ecosystem structure and function [1,3,9,10,24–30].

PJ woodlands of the western US span substantial variations in climate, vegetation structure, and disturbance regimes (Figures 1 and 2, Table 1; [1–4,7,8]). Most of the precipitation in Great Basin PJ woodlands falls during the cold-winter and cool-spring seasons as snow at higher elevations and as rainfall at warmer lower elevations (Figures 1a–c and 2b, Table 1; [1,4,31]). Great Basin PJ woodlands commonly occur as pure stands of western juniper (*J. occidentalis* Hook.) in the northwestern portions of the region and as either pure stands of Utah juniper (*J. osteosperma* [Torr.] Little) or mixed stands of singleleaf pinyon (*P. monophylla* Torr. & Frém.) and Utah juniper throughout the remainder of the region [1,4,8,32]. These woodlands occur as persistent woodlands with moderate to dense tree cover and a sparse shrub and grass understory, or as woodland-encroached shrublands (wooded shrublands) with sparse to moderate tree cover and varying amounts of shrub and herbaceous understory cover [1,2,33,34]. Persistent woodlands in this region mostly occur on rocky uplands with shallow soils, extensive bare ground, and a fire regime of infrequent (100 to >200 year) high severity wildfires [3,31,34]. Wooded shrublands are extensive in the Great Basin in association with pinyon and juniper encroachment into sagebrush-dominated rangelands [2,9,10,12,35–37] and span shallow and rocky to deep productive soils [1–3,33]. Cover of sagebrush and cool-season perennial bunchgrasses dominates early in the pinyon and juniper encroachment gradient, but declines due to competition for limited resources as tree cover increases, particularly on sites with shallow soils [1,2,33,38–42]. Bare ground commonly approaches and exceeds 60% as structural diversity declines on sagebrush rangelands in the later stages of woodland encroachment, often culminating in a barren landscape with isolated litter-covered and nutrient- and organic matter-enriched tree islands and high rates of intercanopy runoff and soil loss [1,27–30,40,43–46]. Large bare areas of PJ woodlands at lower warmer elevations and on warmer aspects in the Great Basin are susceptible to invasion of the fire-prone exotic annual cheatgrass (*Bromus tectorum* L.), particularly following fire [32,47–51]. Soils in PJ woodlands across the Great Basin, as well as the Colorado Plateau, are commonly derived of igneous or sedimentary parent rock. Twoneedle pinyon (*P. edulis* Engelm.) and Utah juniper are the primary overstory trees on PJ woodlands of the Colorado Plateau Region, although Rocky Mountain juniper (*J. scopulorum* Sarg.) also occurs at higher elevations in this area [3,7,8,32,52]. As with the Great Basin, woodlands of the Colorado Plateau commonly occur as persistent woodlands or wooded shrublands and with similar associated understory vegetation dynamics and disturbance regimes [3]. The precipitation regime throughout much of this region is bimodal, with small peaks occurring during the winter- or spring-cool seasons and during the summer-warm season (Figure 1d,e, Table 1; [3–8]). Most precipitation occurs as snowfall for the northwest portion and at higher elevations of the Colorado Plateau (Figure 2b, Table 1). In the southern-most and eastern portions of both the Colorado Plateau and the southwestern US regions, precipitation is dominated by summer-season monsoonal rainfall (Figures 1 and 2b,c, Table 1). The overstory of PJ woodlands in the summer monsoonal climates is dominated by twoneedle pinyon and oneseed juniper (*J. monosperma* [Engelm.] Sarg.), with alligator juniper (*J. deppeana* Steud.) most common at warmer and lower elevations [3,6,7]. Tree cover is often sparse on these woodlands, creating a woodland savanna vegetation type with an understory of warm season grasses and limited shrub cover [3,6,52]. These woodlands commonly occupy fine- to coarse-textured soils from igneous and sedimentary rock that are moderately deep and located on low gradient uplands and in transitional valleys or depositional zones [3,7]. Across all regions, tree cover and the distribution of pinyon and juniper conifers expand and contract with climate fluctuations and disturbance patterns that also affect understory vegetation structure and ecosystem function [1,3,4,7,8,11,13,14,16,17,52–54].

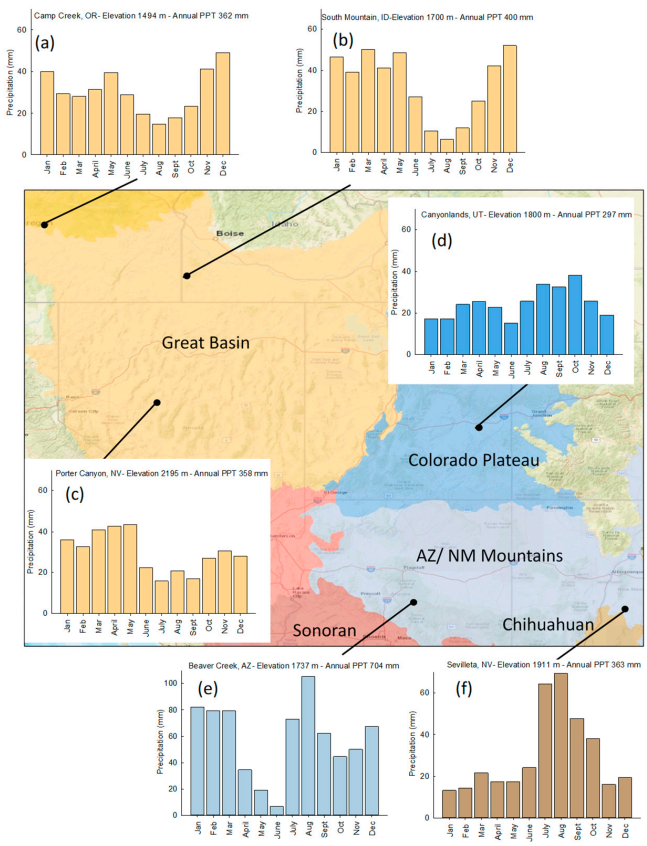

Figure 1. Mean monthly precipitation (PPT) for six selected pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodland study locations listed in Table 1, inclusive of sites with snow-dominated (**a**–**c**), mixed phase (**d**), and rainfall-dominated (**e**,**f**) precipitation regimes and representative of the Great Basin (**a**–**c**), Colorado Plateau (**d**,**e**) and southwestern desert regions (southwestern US, (**f**)) of Arizona (AZ) and New Mexico (NM), USA. Precipitation from 30-year monthly PRISM data (1981–2010) at 800 m resolution [55].

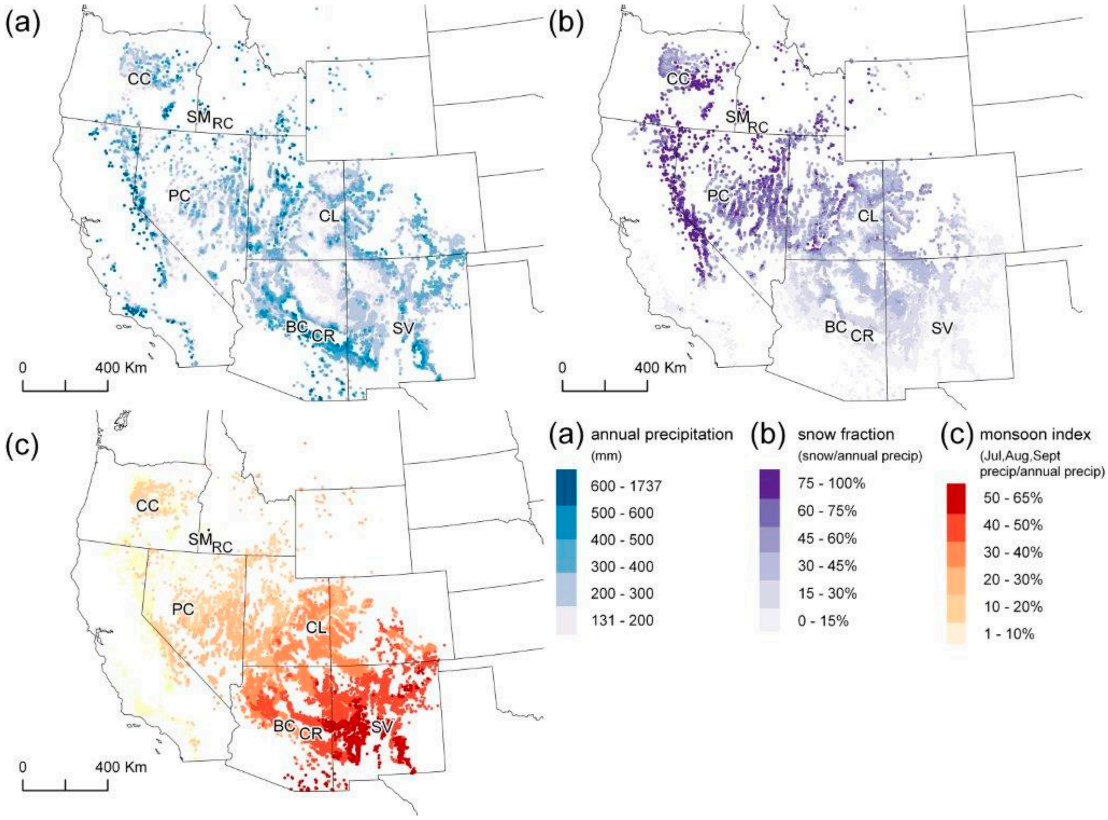

Figure 2. Maps of average mean annual precipitation (**a**), snow fraction ((**b**), percent of annual precipitation as snow), and the monsoon index ((**c**), fraction of the annual precipitation that occurs in July, August and September) across the pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) domain in the western US. Study sites from Table 1 are depicted with site abbreviations.

Table 1. Locations of pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodland study sites plotted in Figures 1 and 2 and associated precipitation regime and respective references. See Figure 1 for region locations in USA. Here, we characterize the Arizona and New Mexico Plateaus Region (i.e., Beaver Creek and Cibecue Ridge sites) as representative of the southern portion of the Colorado Plateau, with a bimodal and rain-dominated annual precipitation regime.

Site Name	State	Latitude	Longitude	Region	Precipitation Regime (Seasonality)	Study
Camp Creek (CC)	OR	43.96° N	−120.34° W	Great Basin	Snow-Dominated, Cool Season	[56,57]
Reynolds Creek (RC)	ID	43.05° N	−116.43° W	Great Basin	Snow-Dominated, Cool Season	[58]
South Mountain (SM)	ID	42.67° N	−116.90° W	Great Basin	Snow-Dominated, Cool Season	[59,60]
Porter Canyon (PC)	NV	39.46° N	−117.62° W	Great Basin	Snow-Dominated, Cool Season	[61]
Canyonlands (CL)	UT	38.83° N	−109.84° W	Colorado Plateau	Mixed-Phase, Bimodal	[62,63]
Beaver Creek (BC)	AZ	34.37° N	−111.42° W	Colorado Plateau	Rain-Dominated, Bimodal	[64,65]
Cibecue Ridge (CR)	AZ	34.01° N	−110.20° W	Colorado Plateau	Rain-Dominated, Bimodal	[66]
Sevilleta (SV)	NM	34.23° N	−106.31° W	Southwestern US	Rain-Dominated, Warm Season	[67,68]

Land managers, scientists, and policy makers are challenged with predicting ecological and economic impacts of tree reductions across the diverse western US pinyon and juniper expanse associated with climate change, increased wildfire activity, and land use. Wildfire activity along the rangeland-dry forest continuum of western US has increased in recent decades and current wildfire trends are projected to persist or amplify in the future due to climate change [69–73]. Much of the interior western US is now in a condition in which rangeland and PJ woodland wildfires fueled by dense woody loading and invasive grasses have a greater likelihood of progressing upslope into dry forests where wildfire activity is also increasing [10,70,72,74–77]. Woody fuel loading of sagebrush rangelands and persistent PJ woodlands through tree infilling across the PJ domain has primed these landscapes for high severity wildfires [10,75,78]. High severity, stand replacement fires are not unprecedented for PJ woodlands, but the frequency of large fires for PJ woodlands in the US has increased substantially in recent years [3,75,79–82]. Wildfire activity in western woodlands and dry forests is dictated by low fuel moisture and cyclonic weather conducive to ignitions and fire spread [76,83–88]. In recent decades, warmer winter and spring air temperature trends at mid-elevations in the western US have resulted in decreased snowpacks [89–94], earlier spring snowmelt and streamflow [90,95–97], and drier fuels [74]. These shifts have lengthened fire seasons and increased fire frequency and area burned [69,74,76,98]. Increased cover of cheatgrass has facilitated greater fire frequency and annual area burned on sagebrush rangelands throughout much of the western US [9,10,75,77]. Cheatgrass promotes wildfire activity on rangelands by increasing the horizontal continuity of fuels and the likelihood of ignition [99,100]. Burning of cheatgrass-infested sites perpetuates cheatgrass dominance and a recurring grass-fire cycle [77,99,101,102]. Fire return intervals in cheatgrass-infested sagebrush rangelands are commonly 10-fold shorter than for intact sagebrush/bunchgrass communities [10]. Abatzoglou and Kolden [70] suggest cheatgrass invasibility and the length of the fire season in the Great Basin will be enhanced by a warmer climate and more frequent wet winters. Cheatgrass is migrating upslope across the interior western US [103–106] and thereby is potentially propagating the cheatgrass-fire cycle at higher elevations into woodlands and dry forests. Cheatgrass occurrence and increases post-fire are already well-documented for PJ woodlands in the Great Basin [32,47,49–51] and elsewhere in the west (e.g., [107–110]). Recent trends of landscape- to regional-scale tree die-off in PJ woodlands throughout the southern Colorado Plateau and southwestern US are expected to continue or increase with climate warming and more frequent drought [13,14,19,23,111–120]. Tree removal practices are being implemented on PJ woodlands across the western US to reduce fuel loading and risk of fire, and to mitigate negative ecological and economic impacts associated with woodland encroachment and infilling [22,28,29,38,41,42,45,46,49–51,108,109,121–133]. These broadly occurring and continuing climate trends, altered disturbance regimes, and management actions on PJ woodlands throughout the western US have important ecohydrologic implications across spatial and temporal scales that vary regionally with climatic gradients [134–138].

In this paper, we summarize the ecohydrologic impacts of pinyon and juniper tree reductions across plot to watershed spatial scales, over short- and long-term periods, and across regional climatic gradients of the western US. We focus on PJ woodlands spanning the Great Basin, Colorado Plateau, and mountainous desert regions of the southwest US (Figures 1 and 2) given the extensive literature on PJ woodlands for these regions. We address three specific research questions: (1) How do tree reductions affect plot- to hillslope-scale ecohydrologic and erosion processes in the short- and long-term across regional climate gradients? (2) Is there a specific climatic (precipitation and/or temperature regime) threshold for increases in water availability (decreases in evapotranspiration and interception losses) with tree reduction, and, if so, (3) Do increases in water availability with tree reduction translate to increases in groundwater and streamflow at the watershed scale? To address these questions, we review substantial literature on PJ woodlands, inclusive of our own research, regarding ecohydrologic and erosion impacts of tree reductions associated with management practices, natural disturbances, and changing climate. The ecohydrology of PJ woodlands and the effects of tree reduction have been well researched, but most studies have focused on isolated hydrologic or erosion processes operating at one or few spatial scales over a short time period for a single site or region. Here, we address these voids through a comprehensive review of literature spanning multiple spatial and temporal scales and climatic zones or regions in the western US and identify key knowledge gaps. We begin with characterization of the ecohydrology of PJ woodlands, built around primary components of the water cycle (precipitation, evapotranspiration, interception, infiltration and soil water recharge, and runoff generation and streamflow) and also address erosion processes therein. Second, we examine the effects of pinyon and juniper reductions on ecohydrologic and erosion processes across spatial and temporal scales and regions within limitations of the literature. The paper concludes with a synthesis of findings to address the research questions above and a brief discussion on climate change implications. Our conclusions include presentation of key knowledge gaps in the current understanding of tree reduction impacts on ecohydrology and erosion processes in PJ woodlands. Our overarching goal is to provide a comprehensive synthesis addressing the impacts of tree reductions on the ecohydrology of PJ woodlands and to thereby address the current need for understanding these impacts in the wake of a changing climate, altered disturbance regimes, and challenging land management objectives spanning the pinyon and juniper woodland domain in the western US.

2. Ecohydrology of PJ Woodlands in the Western US

2.1. Precipitation and Temperature Regimes

Precipitation across the PJ woodland domain of the western US generally amounts to 250 to 600 mm annually, but pinyon and juniper span areas with less and more than these general precipitation thresholds. To illustrate this variability, we plotted estimates of precipitation for multiple research sites spanning the representative PJ woodland domain (Figure 1) and that were subject of studies reviewed in this synthesis (Table 1). The Great Basin Region is a cold desert where much of the precipitation falls as snow and accumulates into a persistent snowpack, with approximately 70% of precipitation received from November to May. Summer precipitation is generally less than 25% of annual total precipitation (Figures 1 and 2). Precipitation for western juniper woodlands throughout the northwestern Great Basin ranges from about 250 mm to 400 mm annually [137], although this species occurs in areas receiving near 180 mm and exceeding 500 mm [1,3]. Average air temperatures for western juniper woodlands range from approximately −6.6 °C in January to 34.5 °C in June and the growing season varies from about 90 to 120 day [2]. There is a summer moisture gradient in the Great Basin with more summer rainfall moving southward and eastward towards the Colorado Plateau (Figure 2). Precipitation across the singleleaf pinyon and Utah juniper domain in the central Great Basin ranges from about 230 mm at low elevations to 600 mm at higher elevations and occurs mostly as snow during the winter and rain during the spring season. Air temperature for this zone averages about −7.2 °C in January and 29.4 °C in July [2]. Further eastward in the Great Basin, annual precipitation averages about 200–250 mm in valley locations, near 300 mm at mid-elevations, and more than 600 mm at the highest elevations [2]. Soil temperature-moisture regimes across the PJ domain in the Great Basin typically span from warm-moist (~8−15 °C annual; >300 mm precipitation annually) at lower elevations and on warmer aspects to cool (~6–8 °C annual)-moist at upper elevations and on cooler aspects [1,2,31], but approach warm-dry (<300 mm precipitation annually) regimes in some areas [125]. The Colorado Plateau has bimodal precipitation, receiving precipitation during the cool winter-spring seasons and the warm monsoon season (Figure 1d; [3]). Some winter precipitation in this region falls as snow and accumulates as persistent snowpack. The precipitation regime in the northwest to central Colorado Plateau is somewhat of an intermediate between the cold desert of the Great Basin and the warm Sonoran and Chihuahuan mountainous deserts in Arizona and New Mexico (Figures 1 and 2). The Sonoran Desert has a bimodal precipitation pattern with nearly equal amounts of precipitation in winter and the summer monsoon seasons (June to Oct) (Figure 2c). The precipitation regime of the Chihuahuan Desert is dominated by summer monsoon rainfall (Figure 2c), with approximately 60% as summer rainfall and less as winter precipitation (Figure 1f). Annual precipitation in the pinyon and juniper zones of the Colorado Plateau and southwestern US ranges from about 200 mm to 700 mm (Figure 2a) depending on elevation and aspect [3,5]. Mean annual air temperature is highly variable across these diverse regions [3], ranging from about 4 °C to 16 °C depending on elevation, and summer season air temperatures can exceed 38 °C. The seasonality of precipitation and temperature regimes in general have been postulated to have important ecohydrological ramifications on pinyon and juniper expansion and on PJ woodland responses to tree reduction treatments, disturbances, and climate change [1,8,11,31,41,42,50,115,134,136,138].

2.2. Evapotranspiration and Interception

Water is one of the most limiting resources to plant growth on PJ woodlands and solar radiation inputs are high [139]. Consequently, evapotranspiration is the dominant component (usually > 90%) of the total water budget for these ecosystems. The percentage of evapotranspiration occurring as transpiration varies considerably (7–80%) for the various plant communities that make up rangelands and woodlands of the western US (see [135,140]) and depends on the amount and timing of precipitation, available energy, plant growth form, and water availability throughout the rooting depth of the soil profile [141–146]. In dry years evapotranspiration in PJ woodlands can exceed precipitation inputs by utilizing water from deep storage [147]. Herein we review components of evapotranspiration for PJ woodlands, including interception, transpiration, and total evapotranspiration.

2.2.1. Interception

Reduction in precipitation inputs due to interception has been posited as a mechanism by which pinyon and juniper expansion leads to ecological degradation and declines in understory vegetation [1,58]. Young et al. [148] estimated 42% of annual precipitation, as measured with rainfall collectors, was intercepted by the canopies of western juniper at a site in the Great Basin. The study assessed interception separately for the winter, spring, summer, and autumn seasons and found no seasonal differences in the percentage of interception of precipitation [148]. Precipitation occurred primarily as snowfall during winter and as intense rain showers in the summer. Eddleman [149] found western juniper canopies with diameters of 2 m, 3 m, and 6 m intercepted 53%, 59%, and 69% of total precipitation, respectively, from a combination of snow and rainfall events. Based on these measures, the author estimated the stand level interception of the woodland would approach 20% of total annual precipitation with 30% tree cover. Eddleman and Miller [150] reported interception of precipitation by western juniper canopies ranged from 44.7% to 63.1% for natural rainfall and snowfall events. Ochoa et al. [57] found canopies of western juniper intercepted about 57–89% of total precipitation from snowfall and rainfall. Interception of total precipitation ranged from 26% to 71% at the whole-plot or stand level based on estimates by measures under tree canopies, in drip line locations, and the intercanopy. In another Great Basin study, Niemeyer et al. [58] used four large weighing lysimeters to measure interception of both rain and snow by western juniper during natural precipitation events. Lysimeters were placed under canopies of two trees and additional lysimeters were placed in intercanopy areas, outside of the canopy and adjacent to the instrumented trees. The ratio of measured under tree canopy to intercanopy surface water input (under canopy/interspace $\times$ 100%) was greater for snow (79.4%) than for rain (54.8%), which was attributed to the wind redistribution of snow under tree canopies. In other words, a greater fraction of water made it below the tree canopy as snow with respect to rainfall through the canopy. Snow accumulation was consistently greater in the intercanopy [58]. Breshears et al. [151] found that snow accumulation during each of three winter seasons was much greater in intercanopy areas between tree canopies than underneath tree canopies at a twoneedle pinyon-oneseed juniper woodland site along the Colorado Plateau. Snow water equivalent in the first year of the three-year study was about 80% greater in the intercanopy openings between trees than in areas underneath canopies. In a rainfall-only study in the Great Basin, Stringham et al. [61] measured liquid rainfall interception at the whole tree level during artificially applied rain storms ranging from 2.2 mm h^{-1} to 25.9 mm h^{-1} applied to individual singleleaf pinyon and Utah juniper trees. There was no difference in interception based on tree species, so results were combined for both species. Interception as a percentage of total rainfall increased with total rainfall applied up to a threshold of about 5 mm and then declined for storms with higher amounts of precipitation. Canopy interception by both species was, on average, 44.6% ($\pm$27%) of total rainfall applied [61]. Stringham et al. [61] used the measured interception data and tree cover data to estimate stand-level interception for two 2450 m^2 stands. Stand-level interception ranged from about 31.5% to 49.1% of total precipitation when tree cover ranged from 31% to 38% [61]. On the Edwards Plateau in Texas, USA, Ashe juniper (*J. ashei* J. Buchholz) was monitored with collection tubes under the canopy for three years at 10 sites, and 2700 rain events were recorded [152]. Average total interception by tree canopies was 35% [152]. Collectively, the studies discussed here suggest tree canopy interception of rainfall and snowfall can range from about 30% to more than 70% for individual trees and at the stand-level for the event and annual temporal scales in PJ woodlands, and that water losses through tree canopy interception thereby can strongly affect the timing and distribution of water availability for soil input for these communities [57–59].

2.2.2. Transpiration

Pinyon and juniper have different water use strategies that have been demonstrated by studies at the leaf level through measured photosynthesis, stomatal conductance, and leaf water potentials [68,153,154]. Pinyon is relatively isohydric, with leaf water potentials being regulated at a fairly conservative minimum stomatal setpoint determined by their vulnerability to xylem cavitation [155]; below this setpoint, stomata will close and photosynthesis will cease. Juniper is relatively ansiohydric and is able to tolerate lower leaf water potentials and keep stomata open, which maintains stomatal conductance and photosynthesis [63]. Juniper will therefore continue to transpire water to the atmosphere during drought conditions for a longer time period than pinyon. Divergence in water use strategies of these two species is demonstrated by differences in minimum leaf water potential. Minimum leaf water potentials reported for twoneedle pinyon and oneseed juniper in the southwestern US and Colorado Plateau range from -2.0 to -2.5 MPa for pinyon and -3.7 to -6.9 MPa for juniper [68,153,154]. The ability of oneseed juniper to withstand drought longer than twoneedle pinyon has also been attributed to the ability of juniper to extract water from deeper in the soil profile. Stable isotope ratios in xylem water of these two species have demonstrated that while both species are able to use summer rain, pinyon is more reliant and responsive to summer rain which increases shallow soil water, whereas juniper extracts a greater proportion of water from deeper in the soil profile [62,63,151,156,157]. It is notable that twoneedle pinyon is replaced by oneseed juniper in the Great Basin, which historically receives very little summer rain.

In a Great Basin study from southern Utah, twoneedle pinyon and Utah juniper relied on similar shallow water sources in the early spring, indicating direct competition with understory species [63]. Twoneedle pinyon was able to upregulate transpiration in response to summer rainfall events that created shallow soil water, while Utah juniper did not. Both species obtained a considerable proportion of water from below shallow soils [63]. This was attributed to their ability to grow deep roots into cracks in bedrock and grow on rock outcrops without significant soil development [158,159]. In general, it appears that twoneedle pinyon is more reliant on summer rainfall than Utah juniper [154,156]. This requires that twoneedle pinyon maintain active shallow roots, which experience greater temperature extremes that may limit this species if temperatures continue to increase. Additional evidence for the presence of shallow roots demonstrated twoneedle pinyon can take up water from intercanopy areas [160]. Further, a study of isotopic evidence contained in 40,000-year-old twoneedle pinyon needles in pack rat middens determined the distribution of twoneedle pinyon was strongly tied to summer rainfall [161].

Transpiration can be measured at the whole tree level by measures of sap flow velocity through xylem tissue [162]. Three studies scaled sap flow velocity to the whole stand level using allometric measurements [63,163,164]. West et al. [63] measured maximum sap flow rates at 0.34 mm day^{-1} and annual total transpiration between 6.5% and 14.5% of total annual precipitation for a site in the Colorado Plateau with 232 mm of average annual precipitation. Approximately 88% of basal tree cover at the site was oneseed juniper and the remaining 12% was twoneedle pinyon [63]. Pangle et al. [164] also found total pinyon and juniper transpiration was low and 11% of annual precipitation over 5 year for a stand with similar basal area of oneseed juniper and twoneedle pinyon and located in the southwestern US with average precipitation of 363 mm. In wet years or irrigated treatments, trees used more water, but still less than 18% of total precipitation [164]. In the studies by West et al. [63] and Pangle et al. [164] understory coverage was minimal, indicating much of the annual precipitation is lost through processes other than plant transpiration, such as interception, evaporation and/or runoff. The third study, Mollnau et al. [163], was located in Oregon in the Great Basin with mean annual precipitation of 320 mm. Mollnau et al. [163] estimated transpiration for a stand of western juniper was 0.4 mm day^{-1} during the summer months [163]. The stand-level estimates from the studies cited herein are on the low end of the range calculated from a canopy diffusion model, which predicts 15–80% transpiration loss from PJ woodlands [165], and highlight the complexities of measuring the water budget and scaling up individual measurements to the stand-level [166].

2.2.3. Total Evapotranspiration

Total evapotranspiration can be measured at the ecosystem level through eddy covariance estimates. Eddy covariance data for Utah juniper suggest the highest evapotranspiration rates, 1.5 mm day^{-1}, occur in March and April, with the remainder of the growing season rates below 1.0 mm day^{-1} [167]. However, ecosystem scale estimates for PJ woodlands are generally lacking in the literature.

2.3. Infiltration, Soil Water, and Runoff Generation

2.3.1. Infiltration and Soil Water Recharge

Infiltration rates and hydraulic conductivities for woodland soils vary across the vast array of soil types and cover conditions which these communities occupy and, for a given site, generally reflect spatial heterogeneity in vegetation and ground cover conditions (Figure 3, Table 2; [27,28,46,51,126,133,168–173]). Wilcox et al. [169] applied infiltrometer methods (76.2-mm diameter) to measure unsaturated and saturated hydraulic conductivities of tuff-derived sandy loam to loam soils at a twoneedle pinyon-oneseed juniper woodland. Saturated hydraulic conductivity was statistically similar for tree canopy areas (150 mm h^{-1}) and intercanopy areas (73 mm h^{-1}) due to high variability. Unsaturated conductivities were greater for tree canopy areas (5–38 mm h^{-1}) than bare interspaces (2–10 mm h^{-1}) across 30, 60, and 150 mm tension infiltrometer measures, with vegetated interspace unsaturated conductivities (3–18 mm h^{-1}) similar to both tree canopy areas and bare interspaces. The saturated and unsaturated hydraulic conductivities reflect wet and dry conditions, respectively, for the soil surface after removal of duff and litter, but with soil crusts intact. Madsen et al. [171] measured unsaturated hydraulic conductivities (15.9-mm diameter disk) and soil water repellency in litter-covered canopy areas underneath Utah juniper and twoneedle pinyon and in intercanopy areas with biological soil crusts. Soils underneath trees were hydrophobic and yielded an average unsaturated hydraulic conductivity of 17.3 mm h^{-1}, with the same measure varying at 4.5, 8.8, 19.1, and 57.5 mm h^{-1} with 0.25, 0.50, 0.75, and 1.00 normalized distance from a tree base (NDTB), respectively. Unsaturated hydraulic conductivity varied substantially for wettable or hydrophilic soils in the intercanopy (125.1 mm h^{-1}, 1.0–3.0 NDTB) and averaged 89.4 mm h^{-1} and 151.8 mm h^{-1}, respectively, for a transitional zone between the tree canopy edge (0.75–1.75 NDTB) and the intercanopy at 1.75–3.0 NDTB. Soil water content averaged 0.08 m^3 m^{-3} in canopy areas, 0.19 m^3 m^{-3} in the intercanopy, and 0.18 m^3 m^{-3} in the intermediate zone. As with the Wilcox et al. [169] infiltrometer study, duff and litter were removed before the experiments, but biological soil crusts were left in place. The trend of higher infiltration rates in canopy areas versus intercanopy areas in the Wilcox et al. [169] study demonstrates the effect of infiltration-inhibiting vesicular crusting on infiltration into interspaces, whereas the reversal in this trend, greater infiltration in intercanopy than canopy areas in the Madsen et al. [171] study, demonstrates the effect of soil water repellency on infiltration into mineral soils on woodland sites. Lebron et al. [170] reported similar findings as Madsen et al. [171] for a Utah juniper woodland and both studies contrast findings of Wilcox et al. [169]. Lebron et al. [170] noted that unsaturated infiltrometer experiments in the Wilcox et al. [169] study were conducted on wetted soils immediately after saturated infiltrometer experiments and therefore may not reflect the effect of soil water repellency on infiltration. Wilcox et al. [169] did not report the presence or absence of soil water repellency, but, as also pointed out by Lebron et al. [170], soil water repellency is more the norm than the exception for soils underneath thick litter layers of juniper and pinyon needles [27,28,30,46,51,126,133,171,174,175]. Neither the Lebron et al. [170] or Madsen et al. [171] studies capture the influences of interception and water storage by the canopy and litter layers in buffering soil water repellency effects on infiltration [27,28,30,46,51,126,133].

A number of rainfall simulation studies from diverse woodland conditions demonstrate the partitioning effect of vegetation and ground cover on water availability for runoff on PJ woodlands (Table 2). Blackburn and Skau [176] reported infiltration rates ranging from 50 to 72 mm h^{-1} for dry and from 43 to 71 mm h^{-1} for wet antecedent soil conditions in singleleaf pinyon-Utah juniper and Utah-juniper woodlands in the Great Basin. Rainfall was applied at 76 mm h^{-1} over a 30 min duration for a range of plot sizes spanning canopy and interspace areas, most 0.91 × 0.91 m in size. Roundy et al. [168] measured infiltration into soils of volcanic parent material on alluvial fans with an overstory of singleleaf pinyon and Utah juniper and with a 5–8% slope (Table 2). Rainfall was applied at 83.8 mm h^{-1} for 1 h to plots ~0.84 m^2 in size and to variable-sized plots with dry and wet antecedent soil conditions. Infiltration rates were similar for dry and wet soil conditions on tree canopy areas (83 mm h^{-1}) and shrub canopy areas (76 mm h^{-1}) respectively, but were substantially lower for interspaces under dry (49 mm h^{-1}) and wet soil conditions (29 mm h^{-1}) in comparison to all canopy areas. In a series of Great Basin companion studies on singleleaf pinyon-Utah juniper, Utah juniper, and western juniper woodlands, Pierson et al. [27,46,126] and Williams et al. [28,51,133] reported average infiltration rates under initially dry soil conditions ranging from 27–50 mm h^{-1} for interspaces, 45–64 mm h^{-1} for tree canopy areas, and 61–64 mm h^{-1} for sagebrush canopy areas. The same studies reported average infiltration rates under initially wet soil conditions ranging from 27–60 mm h^{-1} for interspaces, 68–102 mm h^{-1} for tree canopy areas, and 69–102 mm h^{-1} for sagebrush canopy areas (Table 2). Rainfall was applied to 0.5 m^2 plots at 64 mm h^{-1} for 45 min for the dry soil conditions and 102 mm h^{-1} for 45 min for the wet soil conditions. Soils in the Pierson et al. [27,46,126] and Williams et al. [28,51,133] studies were strongly water repellent underneath pinyon and juniper trees and were wettable underneath shrub canopies and in interspaces. In a companion study to Pierson et al. [27,46,126] and Williams et al. [28,51,133], Cline et al. [172] reported minimum and steady state infiltration rates (102 mm h^{-1} rain intensity, 45 min, wet soils) were nearly three-fold greater for vegetated (48% foliar cover) versus bare (3% foliar cover) interspaces plots (0.5 m^2). Infiltration rates in the studies presented here reflect generally greater infiltration rates on litter-covered soils underneath trees relative to interspace soils on PJ woodlands (Table 2, Figure 4a,b) and demonstrate the effect of the litter layer in buffering soil hydrophobicity effects underneath pinyon and juniper conifers. Likewise, the studies suggest that infiltration rates on PJ woodlands decline with reduction of vegetation and ground cover, as reflected by the generally higher infiltration rates in canopy areas and vegetated interspaces with respect to bare interspace areas. Petersen and Stringham [173] demonstrated these relationships on western juniper sites in the Great Basin. The study applied 102 mm h^{-1} rainfall for 60 min under dry antecedent soil conditions to 0.5 m × 0.5 m intercanopy plots on hillslopes with high (>22%), moderate (13–16%), and low (<3%) western juniper cover. The combination of bare soil and rock cover averaged 94%, 63%, and 23% for high, moderate, and low juniper cover plots, respectively. Steady state infiltration for the low juniper cover hillslopes (90 mm h^{-1}) was ~34% and ~68% greater, respectively, than measured on the moderate (60 mm h^{-1}) and high (29 mm h^{-1}) juniper cover hillslopes. The studies herein clearly demonstrate water available for runoff processes on PJ woodlands accumulates primarily from intercanopy areas (Figure 3a,b) and is likely greatest in bare interspace areas (Figure 3e,f). The infiltration rates presented here and in Table 2 are affected by the rainfall application rates and durations, which vary within natural storms, but provide a basis for understanding the distribution of sink and source areas (or structural-functional relationships) and the potential for runoff generation on PJ woodlands.

Table 2. Site characteristics, infiltration, runoff coefficients, and sediment yields for rainfall simulation and natural rainfall studies in the western US. Modified from Pierson and Williams [135].

Study	Region (Location)—Community Type	Microsite (Plant)	Treatment/Burn Severity (High, Moderate, Low)	Plot Size (m^2)	Slope (%)	Time Since Treatment (mth)	Rain Rate (mm h^{-1})/Duration (min)	Rain Type	WDPT (s) [a]	Soil Water (%) [b]/Conditions	Bare Soil (%)	Canopy Cover (%)	Ground Cover (%)	Avg. Infil-tration (mm h^{-1})	Runoff Coef. (%) [c]	Sed. Yield (g m^{-2})
[177]	Desert Southwest (Sonoran Desert, Arizona, USA)—perennial grassland	Mixed grasses	Unburned	30	1–3	- [d]	Variable	Natural	-	Dry	-	21	-	-	10	1700 [d]
			Moderate	30	1–3	- [d]	Variable	Natural	- [e]	Dry	-	11	-	-	11	2800 [d]
		Mixed grasses	Unburned	30	1–3	- [f]	Variable	Natural	-	Dry	-	37	-	-	14	1800 [f]
			Moderate	30	1–3	- [f]	Variable	Natural	- [e]	Dry	-	29	-	-	14	2200 [f]
[178] [g]	Great Basin (Idaho, USA)—shrub steppe	Sagebrush (*A. tridentata*)	None	32.6	10	-	64/60	Artificial	-	Dry	16	39	84	-	2	5
			None	32.6	6	-	64/60	Artificial	-	Dry	19	12	81	-	11	11
			None	32.6	9	-	64/60	Artificial	-	Dry	45	16	55	-	17	15
[179]	Great Basin (Idaho, USA)—shrub steppe	Shrub canopy area (*A. tridentata*)	None	~0.1	7	-	67/60	Artificial	-	4	0	-	100	-	2	1
		Vegetated interspace	None	~0.1	7	-	67/60	Artificial	-	4	4	-	96	-	23	23
		Bare interspace	None	~0.1	7	-	67/60	Artificial	-	2	94	-	6	-	65	381
[180] [h]	Great Basin (Idaho, USA)—shrub steppe	Shrub canopy area (*A. tridentata*)	Unburned	0.5	35–60	-	67/60	Artificial	-	~14	7	88	93	-	11	2
			Moderate	0.5	35–60	12	67/60	Artificial	-	~5	97	11	3	-	34	30
			High	0.5	35–60	12	67/60	Artificial	-	~5	98	13	2	-	37	22
		Interspace	Unburned	0.5	35–60	-	67/60	Artificial	-	~14	89	18	11	-	24	4
			Moderate	0.5	35–60	12	67/60	Artificial	-	~5	95	16	5	-	26	12
			High	0.5	35–60	12	67/60	Artificial	-	~5	99	5	1	-	49	148
[181]	Great Basin (Nevada, USA)—shrub steppe	Shrub canopy area (*A. tridentata*)	Unburned	0.5	30–40	-	85/60	Artificial	200	7	1	100	99	-	30	12
			High	0.5	30–40	1	85/60	Artificial	102	1	99	1	1	-	37	41
		Interspace	Unburned	0.5	30–40	-	85/60	Artificial	220	5	6	74	94	-	49	24
			High	0.5	30–40	1	85/60	Artificial	97	1	99	4	1	-	30	21
[182]	Colorado Plateau (Pajarito Plateau, New Mexico, USA)—woodland	Vegetated interspace	None	~2	6–12	-	Variable [i]	Natural	-	-	34	-	66	-	25 [i]	298 [i]
		Bare interspace	None	~2	6–12	-	Variable [i]	Natural	-	-	84	-	16	-	37 [i]	1007 [i]
		Tree canopy area (*P. edulis* or *J. monosperma*)	None	1.0	6–12	-	Variable [i]	Natural	-	-	0	-	100	-	8 [i]	39 [i]
[168]	Great Basin (Nevada, USA)—woodland	Shrub canopy area (*A. tridentata*)	Unburned	0.84	5	-	84/60	Artificial	-	Dry	17	-	83	78	-	40
			Burned	0.84	5	1–2	84/60	Artificial	-	Dry	80	-	20	78	-	63
		Interspace	Unburned	0.84	5	-	84/60	Artificial	-	Dry	-	-	-	58	-	93
			Burned	0.84	5	1–2	84/60	Artificial	-	Dry	-	-	-	59	-	67
		Tree canopy area (*P. monophylla* or *J. osteosperma*)	Unburned	0.84	5	-	84/60	Artificial	Rep.	Dry	1	-	99	83	-	5
			Burned	0.84	5	1–2	84/60	Artificial	Rep.	Dry	25	-	75	81	-	18
		Shrub canopy area (*A. tridentata*)	Unburned	0.84	5	-	84/60	Artificial	-	Wet	17	-	83	73	-	57
			Burned	0.84	5	1–2	84/60	Artificial	-	Wet	80	-	20	63	-	105
		Interspace	Unburned	0.84	5	-	84/60	Artificial	-	Wet	-	-	-	38	-	85
			Burned	0.84	5	1–2	84/60	Artificial	-	Wet	-	-	-	33	-	87
		Tree canopy area (*P. monophylla* or *J. osteosperma*)	Unburned	0.84	5	-	84/60	Artificial	Rep.	Wet	1	-	99	83	-	5
			Burned	0.84	5	1–2	84/60	Artificial	Rep.	Wet	25	-	75	75	-	19

Table 2. *Cont.*

Study	Region (Location)—Community Type	Microsite (Plant)	Treatment/Burn Severity (High, Moderate, Low)	Plot Size (m^2)	Slope (%)	Time Since Treatment (mth)	Rain Rate (mm h^{-1})/Duration (min)	Rain Type	WDPT (s) [a]	Soil Water (%) [b]/Conditions	Bare Soil (%)	Canopy Cover (%)	Ground Cover (%)	Avg. Infil-tration (mm h^{-1})	Runoff Coef. (%) [c]	Sed. Yield (g m^{-2})
[168]	Great Basin (Nevada, USA)—woodland	Shrub canopy area (*A. tridentata*)	Unburned	0.84	8	-	84/60	Artificial	-	Dry	10	-	90	80	-	54
			Burned	0.84	8	1–2	84/60	Artificial	-	Dry	45	-	55	80	-	79
		Interspace	Unburned	0.84	8	-	84/60	Artificial	-	Dry	-	-	-	41	-	145
			Burned	0.84	8	1–2	84/60	Artificial	-	Dry	-	-	-	39	-	105
		Tree canopy area (*P. monophylla* or *J. osteosperma*)	Unburned	0.84	8	-	84/60	Artificial	Rep.	Dry	1	-	99	83	-	11
			Burned	0.84	8	1–2	84/60	Artificial	Rep.	Dry	19	-	81	78	-	39
		Shrub canopy area (*A. tridentata*)	Unburned	0.84	8	-	84/60	Artificial	-	Wet	10	-	90	74	-	81
			Burned	0.84	8	1–2	84/60	Artificial	-	Wet	45	-	55	68	-	110
		Interspace	Unburned	0.84	8	-	84/60	Artificial	-	Wet	-	-	-	20	-	182
			Burned	0.84	8	1–2	84/60	Artificial	-	Wet	-	-	-	25	-	219
		Tree canopy area (*P. monophylla* or *J. osteosperma*)	Unburned	0.84	8	-	84/60	Artificial	Rep.	Wet	1	-	99	82	-	10
			Burned	0.84	8	1–2	84/60	Artificial	Rep.	Wet	19	-	81	66	-	60
[45]	Great Basin (Oregon, USA)—woodland	Intercanopy	None	32.5	19	-	55/60	Artificial	-	Wet	84	6	16	-	25	118
		Intercanopy—trees removed [j]	Cut	32.5	19	-	55/60	Artificial	-	Wet	64	23	36	-	2	1
[183]	Great Basin (Idaho, USA)—shrubland-woodland	Shrub canopy area (*A. tridentata*)	Unburned	0.5	35–50	-	85/60	Artificial	286	7	2	84	98	-	39	17
			Moderate-High	0.5	35–50	1	85/60	Artificial	261	3	42	10	58	-	76	183
		Interspace	Unburned	0.5	35–50	-	85/60	Artificial	110	3	25	31	75	-	63	195
			Moderate-High	0.5	35–50	1	85/60	Artificial	117	4	84	0	16	-	55	705
[183]	Great Basin (Idaho, USA)—shrubland-woodland	Intercanopy	Unburned	32.5	35–50	-	85/60	Artificial	-	2	24	57	76	-	4	8
			Moderate-High	32.5	35–50	1	85/60	Artificial	208	4	76	0	24	-	27	988
[28,46]	Great Basin (Idaho, USA)—woodland	Shrub canopy area (*Artemisia* spp.)	Unburned	0.5	20	-	102/45	Artificial	<5	Wet	25	117	75	69	20	6
			High	0.5	18	11	102/45	Artificial	11	Wet	57	21	43	72	23	143
		Interspace	Unburned	0.5	14	-	102/45	Artificial	<5	Wet	46 [k]	20	54	38	63	36
			High	0.5	16	11	102/45	Artificial	<5	Wet	49 [k]	21	51	50	51	135
		Tree canopy area (*J. occidentalis*) [l]	Unburned	0.5	21	-	102/45	Artificial	42	Wet	0	17 [l]	100	77	23	6
			High	0.5	17	11	102/45	Artificial	54	Wet	50	5 [l]	50	43	58	206
		Intercanopy	Unburned	13	19	-	102/45	Artificial	-	Wet	28 [m]	18	72	58	50	272
			High	13	16	11	102/45	Artificial	-	Wet	39 [m]	32	61	58	50	572
		Tree canopy area (*J. occidentalis*) [l]	Unburned	13	16	-	102/45	Artificial	Rep.	Wet	7	26 [l]	93	106	13	48
			High	13	18	11	102/45	Artificial	Rep.	Wet	25	15 [l]	75	47	58	1083
[27, 127]	Great Basin (Nevada, USA)—woodland	Intercanopy	Unburned	13	9	-	64/45	Artificial	-	6	26 [n]	39	74	46	24	45
			High	13	9	10	64/45	Artificial	-	1	70 [n]	23	30	60	6	25
		Tree canopy area (*P. monophylla* or *J. osteosperma*) [l]	Unburned	13	9	-	64/45	Artificial	Rep.	11	3	27 [l]	97	53	3	18
			High	13	9	10	64/45	Artificial	Rep.	2	19	6 [l]	81	59	1	6
		Intercanopy	Unburned	13	9	-	102/45	Artificial	-	Wet	26 [n]	39	74	57	47	222
			High	13	9	10	102/45	Artificial	-	Wet	70 [n]	23	30	61	40	346
		Tree canopy area (*P. monophylla* or *J. osteosperma*) [l]	Unburned	13	9	-	102/45	Artificial	Rep.	Wet	3	27 [l]	97	102	5	36
			High	13	9	10	102/45	Artificial	Rep.	Wet	19	6 [l]	81	92	13	78

Table 2. *Cont.*

Study	Region (Location)—Community Type	Microsite (Plant)	Treatment/Burn Severity (High, Moderate, Low)	Plot Size (m^2)	Slope (%)	Time Since Treatment (mth)	Rain Rate (mm h^{-1})/Duration (min)	Rain Type	WDPT (s) [a]	Soil Water (%) [b]/Conditions	Bare Soil (%)	Canopy Cover (%)	Ground Cover (%)	Avg. Infil-tration (mm h^{-1})	Runoff Coef. (%) [c]	Sed. Yield (g m^{-2})
[27, 127]	Great Basin (Utah, USA)—woodland	Intercanopy	Unburned	13	14	-	64/45	Artificial	-	7	29 [o]	19	71	58	10	37
			High	13	19	10	64/45	Artificial	-	7	43 [o]	17	57	57	6	41
		Tree canopy area (*J. osteosperma*) [l]	Unburned	13	15	-	64/45	Artificial	Rep.	9	8	21 [l]	92	64	2	13
			High	13	19	10	64/45	Artificial	Rep.	6	41	3 [l]	59	50	21	448
		Intercanopy	Unburned	13	14	-	102/45	Artificial	-	Wet	29 [o]	19	71	66	44	296
			High	13	19	10	102/45	Artificial	-	Wet	43 [o]	17	57	56	41	491
		Tree canopy area (*J. osteosperma*) [l]	Unburned	13	15	-	102/45	Artificial	Rep.	Wet	8	21 [l]	92	112	10	66
			High	13	19	10	102/45	Artificial	Rep.	Wet	41	3 [l]	59	55	52	1893
[126]	Great Basin (Nevada, USA)—woodland	Shrub canopy area (*Artemisia* spp.)	Unburned	0.5	11	-	102/45	Artificial	<5	Wet	12	93	88	93	4	6
			High	0.5	13	10	102/45	Artificial	<5	Wet	49	53	51	81	10	48
		Interspace	Unburned	0.5	9	-	102/45	Artificial	<5	Wet	44 [p]	33	56	60	41	23
			High	0.5	10	10	102/45	Artificial	<5	Wet	49 [p]	30	51	54	46	41
		Tree canopy area (*P. monophylla* or *J. osteosperma*)	Unburned	0.5	12	-	102/45	Artificial	48	Wet	0	7 [q]	100	102	0	0
			High	0.5	15	10	102/45	Artificial	65	Wet	9	4 [q]	91	68	28	46
[126]	Great Basin (Utah, USA)—woodland	Shrub canopy area (*Artemisia* spp.)	Unburned	0.5	17	-	102/45	Artificial	<5	Wet	18	69	82	91	8	33
			High	0.5	16	10	102/45	Artificial	<5	Wet	44	28	56	63	29	220
		Interspace	Unburned	0.5	19	-	102/45	Artificial	<5	Wet	52 [r]	19	48	45	56	233
			High	0.5	16	10	102/45	Artificial	<5	Wet	38 [r]	7	62	37	64	351
		Tree canopy area (*J. osteosperma)*	Unburned	0.5	20	-	102/45	Artificial	88	Wet	7	22 [q]	93	70	22	98
			High	0.5	21	10	102/45	Artificial	125	Wet	9	2 [q]	91	76	18	294

[a] Water drop penetration time (WDPT) is an indicator of persistence and strength of soil water repellency as follows: <5 s wettable, 5 to 60 s slightly repellent, 60 to 600 s strongly repellent [184]. "Rep." indicates authors reported water repellent soil conditions, but did not specifically provide a WDPT or other quantitative measure of soil water repellency for respective plots. [b] Measured near the soil surface (<5 cm depth). [c] Runoff coefficient is equal to cumulative runoff divided by cumulative rainfall applied. Value is multiplied by 100 to obtain percentage. [d] Cumulative runoff and sediment yield for period of 1 July 1998 to 1 October 1998 resulting from natural rainfall events (100 mm). Fire was in May 1998. [e] Informal water drop tests showed no postfire soil water repellency at soil surface [177]. [f] Cumulative runoff and sediment yield for period of 1 July 1999 to 1 October 1999 resulting from natural rainfall events (106 mm). Fire was in May 1998. [g] Data shown are for experiments on initial dry conditions (dry run) and natural plots (untreated) at Coyote Butte, Nancy, and Summit sites, respectively by row. [h] Data presented from south-facing slopes solely. [i] Runoff and erosion following natural rainfall events were monitored over a 26-month period. [j] *J. occidentalis* trees removed from site by chainsaw cutting 10 years before rainfall simulation experiments. [k] Bare ground was about 90 percent across unburned (42 percent rock and 46 percent bare soil) and burned (43 percent rock and 49 percent bare soil); ground cover includes rock cover (and ash for burned plots). [l] Trees removed from plot by chainsaw immediately before simulations. [m] Bare ground was about 88 percent (60 percent rock and 28 percent bare soil) for unburned and 88 percent (45 percent rock, 4% ash, and 39 percent bare soil) for burned; ground cover includes rock cover (and ash for burned plots). [n] Bare ground was about 64 percent (38 percent rock and 26 percent bare soil) for unburned and about 86 percent (16 percent rock, <1 percent ash, and 70 percent bare soil) for burned; ground cover includes rock cover (and ash for burned plots). [o] Bare ground was about 79 percent (50 percent rock and 29 percent bare soil) for unburned and about 81 percent (38 percent rock, <1 percent ash, and 43 percent bare soil) for burned; ground cover includes rock cover (and ash for burned plots). [p] Bare ground was about 73 percent (29 percent rock and 44 percent bare soil) for unburned and 87 percent for burned (38 percent rock and 49 percent bare soil); ground cover includes rock cover (and ash for burned plots). [q] Trees removed from plot about 12 months before simulation as part of earlier study [27]. [r] Bare ground ≥90 percent across unburned (38 percent rock cover and 52 percent bare soil) and burned (56 percent rock cover and 38 percent bare soil); ground cover includes rock cover (and ash for burned plots).

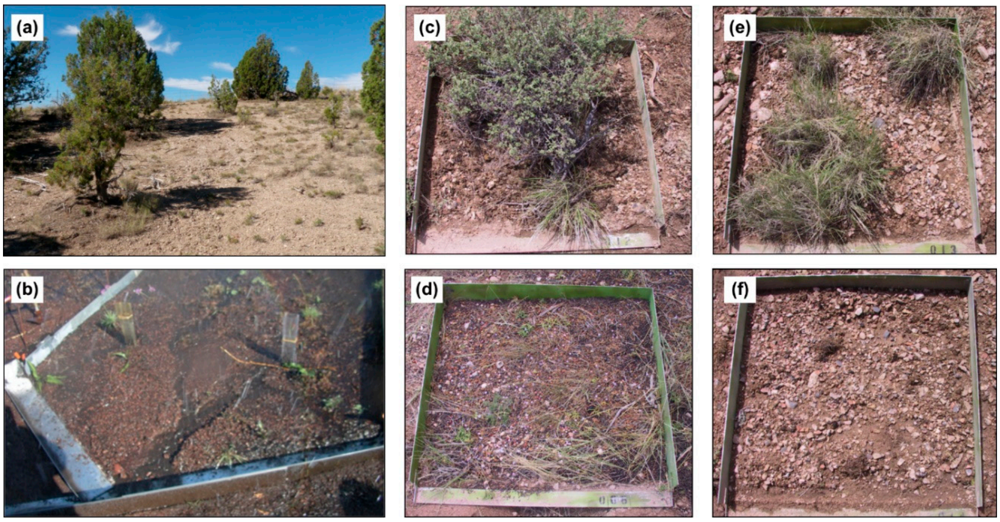

Figure 3. Photographs of a Utah juniper (*J. osteosperma* [Torr.] Little) woodland showing the patchy structure of tree-covered area and bare intercanopy between trees (**a**), a bare intercanopy runoff plot with concentrated overland flow and rilling (**b**), and shrub (**c**), under tree canopy (**d**), grass covered interspace (**e**), and bare interspace (**f**) microsites. Figure modified from Pierson and Williams [135] and Miller et al. [4].

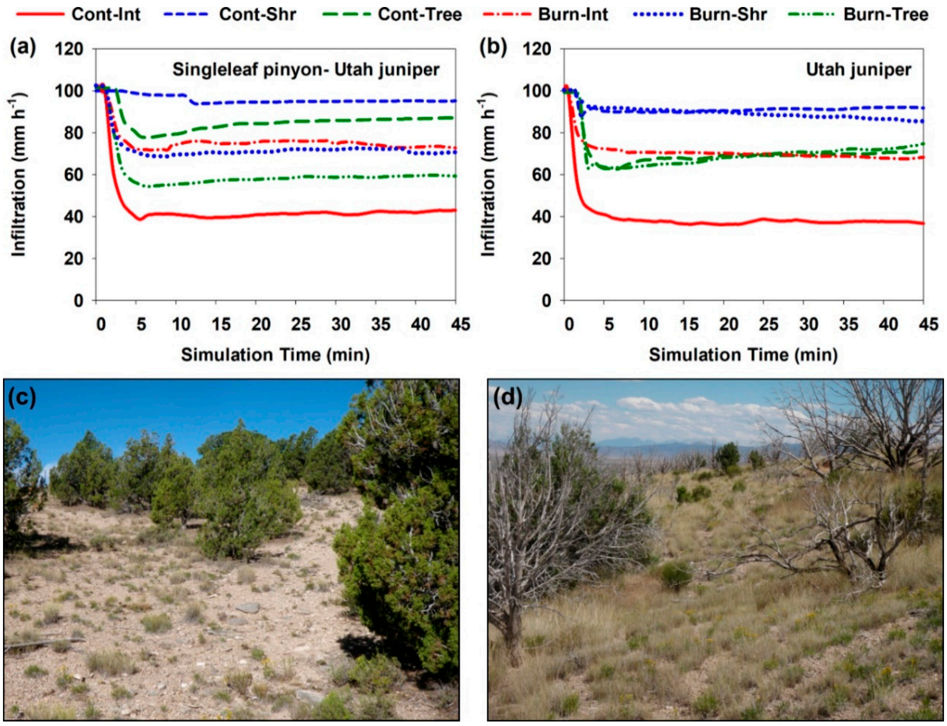

Figure 4. Infiltration (**a**,**b**) from rainfall simulation experiments (102 mm h^{-1}, 45 min, 0.5 m^2 plots) in untreated interspaces between shrubs and trees (Cont-Int), untreated shrub (Cont-Shr) and tree (Cont-Tree) canopy areas, burned interspaces (Burn-Int), and burned shrub (Burn-Shr) and tree (Burn-Tree) canopy areas in a singleleaf pinyon (*P. monophylla* Torr. & Frém.)-Utah juniper (*J. osteosperma* [Torr.] Little) woodland (**a**) and a Utah juniper woodland (**b**) 9 year after prescribed fire. Photographs at bottom of figure show the untreated Utah juniper woodland with extensive intercanopy area comprised primarily of bare interspace and limited shrub cover (**c**) and the same site 9-year post-fire with well-distributed intercanopy herbaceous cover (**d**). Data from Williams et al. [51]. Figure modified from Miller et al. [4].

Several authors have postulated that soil water repellency underneath pinyon and juniper canopies may provide water conservation and increased plant productivity for these conifers (170,171,174). Lebron et al. [170] and Madsen et al. [171] observed that surface water on hydrophobic soils under Utah juniper and twoneedle pinyon canopies bypassed the water repellent layer into deeper soil layers via preferential flow in isolated wet spots. Robinson et al. [174] found soil water repellency under Utah juniper and twoneedle pinyon concentrated infiltration of summer precipitation into undercanopy soils via preferential flow. Roundy et al. [168] characterized a similar behavior to explain rapid infiltration of simulated rainfall into hydrophobic soils underneath Utah juniper (Table 2). Water availability deep in the soil profile favors woody plants and increases plant productivity through enhanced water availability and transpiration rates [29,143,166,185]. Therefore, surface flow routing by soil water repellency may function similar to the lateral surface transfers of overland flow (runon) in maintaining shrub and woodland tree patches of higher biological activity and water retention [143,151,166,174,182,185–187]. Overall, soil water in PJ woodlands is affected by above- and below-ground physical and biological attributes that regulate spatial variability in water input, storage, and use [56,57,59,151,160,163,188].

Vegetation structure on PJ woodlands can influence soil water availability and moderate the soil microclimate through shading solar radiation and insulating surface soils [151,160,170,188,189]. Breshears et al. [151] found that intercanopy areas between tree canopies of a twoneedle pinyon-oneseed juniper woodland in the Colorado Plateau had 40% to 50% more near-surface solar radiation than areas underneath tree canopies, and that preferential shading on the northern side of tree canopies significantly reduced near-surface solar radiation. Snow water equivalent was greater in intercanopy locations than under tree canopies and the differential accumulation resulted in temporal variability in the spatial arrangement of soil water. Soils in tree canopy areas were wetter than intercanopy soils in early winter following snowmelt and during the monsoon rainy season immediately after runoff events. Wetter soil conditions on the edges of canopy areas compared to intercanopy locations following monsoon rain events were assumed partially related to runoff transfers from the intercanopy to canopy areas. Intercanopy soils were wetter than canopy area soils later in the winter and in early spring during the intercanopy snowmelt period. The differential snow accumulation and melt patterns, related in large part to canopy snow interception, exerted a greater influence on the spatial distribution of soil water than did effects of preferential shading [151]. The main effect of solar radiation on soil moisture patterns was observed within intercanopy patches, where north edges with greater solar radiation were wetter than the shaded south edges during winter and spring. Breshears et al. [188], working at the same site as Breshears et al. [151], found that maximum air temperature was as much as 10 °C greater in the intercanopy than in tree canopy areas during late spring through summer and that the associated differences in spatial temperature resulted in differences in soil evaporation. The authors suggested that spatial differences in soil temperature affected soil evaporation only when soils were thawed and were amplified at lower soil water contents.

2.3.2. Runoff Generation

Plot scale studies have demonstrated that the amount and type of runoff, as well as the continuity of runoff sources, along a woodland hillslope are largely determined by magnitude of water input and the amount and connectivity of bare ground (Figure 5; [24,27–30,45,46,51,127,132,133,166,182,190,191]). Runoff from tree canopy areas in PJ woodlands is often minor relative to that of the intercanopy due to precipitation interception and water storage in the canopy and litter layers (Figure 5, Table 2; [27,28,30, 46,51,126,133,166,182]). In contrast, runoff generated in bare intercanopy areas (Figures 3 and 5,b) on PJ woodlands is the primary source for runoff accumulation downslope unless captured by nearby vegetated or litter-covered patches [25,27,28,30,45,46,51,133,166,182,185]. Pierson et al. ([27], Table 2) found that runoff from bare interspace areas on 13 m^2 rainfall simulation plots within the intercanopy at two sloping (10–15%) Great Basin PJ woodland sites facilitated concentrated flow during high intensity rainfall application (102 mm h^{-1}, 45 min). Total runoff from the same simulated storm on

0.5 m^2 interspace plots was similar to the total runoff measured on 13 m^2 intercanopy plots, but runoff on the larger plots occurred mainly as high velocity concentrated overland flow. Similar results were reported by Pierson et al. [46] and Williams et al. [28] for a sloping (10–25%) western juniper woodland in which the same methodologies as Pierson et al. [27] were applied (Table 2). Pierson et al. [27,46] and Williams et al. [28] reported mean intercanopy runoff rates of 6–14 mm h^{-1} for 64 mm h^{-1} rainfall intensity on dry soils and 50–57 mm h^{-1} for 102 mm h^{-1} rainfall intensity on wet soils over a 45 min duration to 13 m^2 plots (Table 2). Collectively, these studies demonstrate that intercanopy runoff from high intensity storms in Great Basin PJ woodlands is largely controlled by the amount of bare ground (bare soil and rock) and increases where bare ground exceeds 50–60% (Figure 5). In another Great Basin study, Pierson et al. ([45], Table 2) found that large patches of bare interspace (average 91% bare ground) on 32.5 m^2 intercanopy plots at a sloping (19%) western juniper woodland promoted concentrated overland flow during a 55 mm h^{-1} applied rainfall event of 60 min duration (Table 2). Runoff averaged about 1, 3, 5, 8, and 14 mm h^{-1} at 5, 10, 15, 30, and 60 min into the simulations, representative of 2-, 4-, 8-, 50-, and 100-year return-interval rainfall events, respectively [45]. Wilcox [190] reported that 10–18% of the annual water budget for a New Mexico PJ woodland (southern Colorado Plateau) over a 2-year period was converted to runoff on gently sloping (5%) 30-m^2 intercanopy plots (undisturbed plots only). The largest runoff events primarily occurred during intense summer thunderstorms, but runoff also occurred during late winter snowmelt events. Wilcox [190] noted that both winter snowmelt and rain-on-snow and summer thunderstorm events commonly generate plot-scale runoff in PJ woodlands of northern New Mexico, but that, for these mountainous locations, hillslope runoff risk is likely greatest during high intensity summer monsoon thunderstorm events. Reid et al. [182] measured seasonal runoff from natural rainfall in intercanopy and canopy areas of a sloping (~10%) twoneedle pinyon-oneseed juniper woodland (southern Colorado Plateau) over a 26-month period (Table 2). A substantial portion (37%) of the precipitation from rainfall events was converted to runoff in bare intercanopy patches and 12% of the precipitation from these areas was re-captured as runon downslope in vegetated intercanopy patches. Tree canopy patches covered 50% of the study site and intercanopy areas were a mosaic of patches, some devoid of vegetation and some with relatively dense vegetation. Bare patch connectivity was limited and there was limited indication of rills at the site [182]. The studies by Pierson et al. [27,45,46] and Williams et al. [28] and that of Reid et al. [182] discussed above contrast in that the former document runoff responses for PJ woodlands with extensive, well-connected intercanopy bare ground and ample runoff and the latter documents considerable capture of runoff as runon within an intercanopy with limited bare ground connectivity. Wilcox et al. [166] characterized PJ woodlands, such as in the Pierson et al. [27,45,46] and Williams et al. [28] studies, with extensive bare ground connectivity and high runoff rates as "non-conserving" or "leaky" and those as in the Reid et al. [182] study with limited bare ground as "resource conserving". Clearly, both conditions exist across PJ woodlands of the Great Basin, Colorado Basin, and southwestern US and therefore hillslope runoff behavior is quite variable across this vast domain. However, the general non-linear trend of increasing patch-scale to hillslope runoff contributions with increasing bare ground and intercanopy connectivity (e.g., Figure 5) is likely common for runoff-generating storms on these landscapes [24,25,27–30,46,166,192,193].

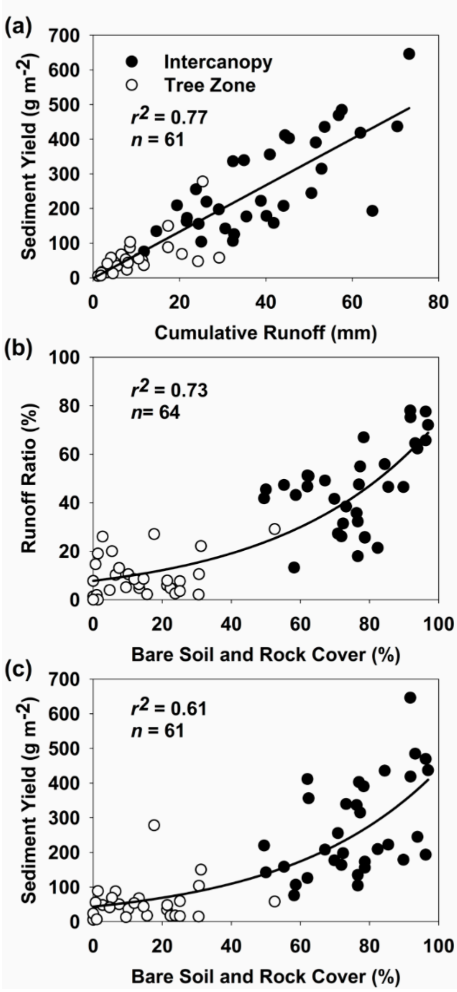

Figure 5. Sediment yield versus cumulative runoff (**a**), the runoff ratio versus bare ground (bare soil and rock, (**b**)), and sediment yield versus bare ground (**c**) for rainfall simulation experiments (102 mm h^{-1}, 45 min, 13 m^2 plots) in intercanopy areas (Intercanopy) between trees and in tree canopy areas (Tree Zones) of western juniper (*J. occidentalis* Hook.), Utah juniper (*J. osteosperma* [Torr.] Little), and singleleaf pinyon (*P. monophylla* Torr. & Frém.)-Utah juniper woodlands in the Great Basin. The graphs clearly depict that sediment delivery from these systems is well correlated to the amount of runoff generated and that both runoff and sediment yield are well correlated with percent bare ground. Data from Pierson et al. [27,46] and Williams et al. [28].

2.4. Streamflow

Seasonal variation in runoff from PJ woodlands is largely controlled by the prevailing precipitation regime [140,166,190]. The highest runoff rates from snow-dominated PJ woodlands in the Great Basin and Colorado Plateau occur during the snowmelt period or during rain-on-snow events [57,59,60]. For rangelands and woodlands in these climates, snowmelt runoff is generated mainly from subsurface return flow in or near stream channels [194,195] and the timing and amount of streamflow are strongly governed by the amount and distribution of snow [59,94,196–198]. Runoff at low- to mid-elevation sites in the Great Basin occurs commonly as saturated overland flow due to rainfall on shallow snowpacks and frozen soils during winter and spring months or as infiltration-excess overland flow during infrequent short-duration, high intensity rainfall events in summer months [199,200]. In the southwestern US, most mountainous locations present intermediate precipitation-runoff patterns, in contrast with the purely snow-dominated or rainfall-dominated Great Basin and Colorado Plateau uplands [140,166]. Such sites may exhibit both winter and summer precipitation-runoff regimes, but the largest runoff events are usually related to intense monsoon summer thunderstorms resulting in infiltration-excess overland flow [166,190].

Watershed-scale studies on runoff from PJ woodlands are more limited than plot-scale to hillslope-scale studies. Kormos et al. [60] summarized hydrologic data collected over a period of six years for four western juniper-dominated (42–61% juniper canopy cover) experimental watersheds in Idaho, USA (northern Great Basin). The watersheds range in size from 21–70 ha and span hillslope gradients of ~20%. Annual precipitation at the sites (627 mm) occurs primarily during the winter and spring seasons and is therefore dominated (53–76%) by snowfall and mixed-phase events typical of northern Great Basin Region [60]. Streamflow at the sites is intermittent in response to snowmelt and rain-on-snow events, usually ceasing in late spring to mid-summer [60]. Average annual streamflow across the four watersheds for the period of record was 115 mm, or about 18% of the mean annual precipitation for the same period [60]. Wilcox [190] provides a summary of numerous early (1960s–1980s) watershed-scale (24 ha to >60,000 ha) runoff studies for PJ woodlands in the southern Colorado Plateau and southwestern US with winter- and summer-dominated precipitation regimes. The summary therein reports runoff ranged from 2–23% of the annual precipitation (283–526 mm) for the studies reviewed, but that runoff from southwestern US PJ woodlands generally amounts to <10% of annual water budget [190]. Wilcox [190] further noted that evapotranspiration is the dominant water-loss mechanism on southwestern US PJ woodlands, that streamflow from these woodlands is typically ephemeral, and that the seasonality of runoff for these landscapes is strongly related to the precipitation regime, with winter flows more common on snowy uplands and high summer flows occurring following intense summer thunderstorms. Collectively, the Wilcox [190] and Kormos et al. [60] studies characterize watershed-scale runoff responses common to PJ woodlands at the annual time scale spanning the snow-dominated, mixed-phase, and rain-dominated precipitation regimes [56,57,59,136,166,201]. Although streamflow amounts to only a small portion of the annual water budget for these systems (<10% to ~20%) [60,166,190], the patchy structure of PJ woodlands, particularly where degraded, exhibits limited buffering capacity to the most intense storms and can be subject to extreme runoff events [202].

2.5. Erosion Processes

Rainfall simulation experiments from PJ woodlands provide reasonable estimates of woodland splash-sheet erosion at fine spatial scales (Table 2). Blackburn and Skau [176] applied rainfall at 76 mm h^{-1} over a 30 min duration to plots of various sizes spanning canopy and interspace areas in PJ woodlands in the Great Basin. The authors reported sediment yields ranging near 0 g m^{-2} to 94 g m^{-2} for initially dry soil conditions and near 0 g m^{-2} to 139 g m^{-2} for initially wet soil conditions across a diversity of soils. In a singleleaf pinyon-Utah juniper woodland (Great Basin), Roundy et al. [168] found splash-sheet erosion from volcanic soils was substantially higher for interspaces (85–182 g m^{-2}) relative to shrub canopy areas (40–81 g m^{-2}) and tree canopy areas (5–11 g m^{-2}) during 84 mm h^{-1} rainfall simulations applied for 1 h across dry and wet antecedent moisture conditions (Table 2). Rainfall simulation studies by Pierson et al. [27,46,126] and Williams et al. [28,51,133] likewise reported higher splash-sheet erosion levels for interspaces than shrub and tree canopy areas across multiple sloping (10–25%) PJ woodlands sites in the Great Basin spanning soils from volcanic to sedimentary parent rocks (Table 2). The studies applied rainfall rates on 0.5 m^2 plots at 64 mm h^{-1} for 45 min for dry soil conditions and 102 mm h^{-1} for 45 min for the wet soil conditions. The authors reported average sediment yields for initially dry soil conditions ranging from 7–126 g m^{-2} for interspaces, 0–53 g m^{-2} for tree canopy areas, and 0–9 g m^{-2} for sagebrush canopy areas. The same studies reported sediment yields for initially wet soil conditions ranging from 36–381 g m^{-2} for interspaces, 0–174 g m^{-2} for tree canopy areas, and 0–48 g m^{-2} for sagebrush canopy areas. The wide range in values for a given microsite (interspace, tree canopy, shrub canopy) and soil moisture condition (dry, wet) reflect different soil erodibilities across the study sites associated with the varying soil types, with soils derived of sedimentary rock (limestone and sandstone) having the highest erodibility [27]. The generally higher sediment yields from interspaces are due to higher bare soil exposure and runoff for interspace areas relative to the tree and shrub canopy areas (Table 2; [27,28,46,51,126,133]). A western juniper woodland (Great Basin) study by Petersen and Stringham [173] measured sediment yields from intercanopy rainfall simulations on hillslopes representing a gradient of juniper dominance and bare conditions. The study found that 1-h rainfall simulations on 0.5 m $\times$ 0.5 m plots at a 102 mm h^{-1} intensity produced more than three-fold more sediment from bare intercanopy plots (1007 g m^{-2}) than vegetated intercanopy plots (298 g m^{-2}) on soils derived from volcanic parent rock. Cline et al. [172], using the same methodologies as described for Pierson et al. [27] above, also reported a two- to three-fold greater sediment yield for 64 mm h^{-1} and 102 mm h^{-1} rainfall simulations from bare (62 and 313 g m^{-2}) than vegetated (16 and 133 g m^{-2}) interspaces at Utah juniper woodland in the Great Basin. The studies cited above clearly depict the typical distribution of sediment sources on PJ woodlands, with sediment primarily generated from bare and vegetated interspaces and overall erodibility varying with soil type [27,28,30,51,72,133,166,172,193,203].

Findings from plot-scale studies underscore that the potential for cross-scale sediment delivery on PJ woodlands during runoff-generating storms is largely controlled by the amount and connectivity of bare intercanopy area ([27,28,30,45,46,51,133,166,182]; Figure 5). As previously discussed, interspaces on PJ woodlands are the primary sources for runoff and sediment (Table 2), and, where well connected, these sources accumulate in concentrated flow paths (Figure 3b) with high flow velocity, erosive energy, and sediment transport capacity [27–29,45,51,133,203–206]. Pierson et al. ([45], Table 2) reported sediment yields of 1, 4, 8, 30, and 118 g m^{-2} at 5, 10, 15, 30, and 60 min, respectively, during rainfall simulations on 32.5 m^2 intercanopy plots at an application rate of 55 mm h^{-1} in a western juniper woodland. The authors found that runoff from bare interspaces during concentrated flow experiments facilitated high flow velocities (~0.10 m s^{-1}) and sediment concentrations (2.21–2.58 g L^{-1}). Similar Great Basin studies from Utah juniper, singleleaf pinyon-Utah juniper, and western juniper woodlands by Pierson et al. [27,46,127] and Williams et al. [28,30] found intercanopy sediment yield from high intensity rainfall simulations (13 m^2 plots) increased non-linearly with bare ground where bare ground exceeded 50–60% due to formation of high velocity concentrated flow paths (Figure 5c). Those studies reported intercanopy flow velocities ranging from 0.06 to 0.20 m s^{-1} for concentrated flow experiments with flow releases of approximately 15, 30, and 45 L min^{-1}. High runoff rates on intercanopy plots during rainfall simulation experiments in the study transported interspace-generated sediment downslope in concentrated flow resulting in cumulative sediment yields ranging from 36 to 45 g m^{-2} and 154 to 401 g m^{-2} for simulations at 64 mm h^{-1} (dry conditions) and 102 mm h^{-1} (wet conditions) intensities, respectively, over 45 min durations [27,28,30,46,127]. In contrast, concentrated flow paths were limited on litter-covered tree canopy areas and sediment yield from the same simulations on those plots ranged from 10 to 18 g m^{-2} and 36 to 78 g m^{-2} for the lower and higher intensity rates, respectively [27,28,30,46,127]. Pierson et al. [27,46] and Williams et al. [28,30] found that intercanopy sediment yield increased with increased plot scale (from 0.5 m^2 to 13 m^2) even though runoff rates were similar across plot scales. The authors attributed the increased sediment delivery across spatial scales within the intercanopy to the concentration of overland flow at the larger plot scale, indicative of a "non-conserving" or "leaky" system as described for degraded woodlands in the southern Colorado Plateau [24,25,166]. Reid et al. [182] and Wilcox et al. [166] describe conditions measured in "resource-conserving" woodlands whereby isolated runoff from bare patches is captured in downslope vegetated patches and hillslope sediment loss is limited. Wilcox [190] found that erosion from PJ woodlands in the southern Colorado Plateau is generally higher in the summer in association with high-intensity monsoonal thunderstorm events relative to the winter-season runoff from snowmelt with no raindrop impact. That study reported summer season sediment yields ranging 1–287 g m^{-2} and winter season sediment yields ranging 1–11 g m^{-2} for 30 m^2 natural runoff plots (5% slope, 15% bare ground, undisturbed plots only) over a two-year period [190]. Annual watershed-scale erosion estimates for PJ woodlands are largely absent from the literature and can vary greatly with land use and disturbance, topography, and soil type (~20–100 g m^{-2}; see [24,66,121,166,191,207]), so current estimates are heavily biased by a few studies. Overall, hillslope contributions of sediment to channels and the watershed-scale are dictated by the runoff and sediment source and sink structure and are greatest for high magnitude runoff events on sites with well-connected bare intercanopy area (50–60% bare ground) and an ample sediment supply [24,25,28,30,72,166,190,191,193].

3. Tree Reduction Impacts on PJ Woodland Ecohydrology and Erosion

3.1. Fire Impacts

The consumption of canopy and ground cover by fire reduces interception capacity and surface water retention and increases the intensity and quantity of water arrival at the soil surface and the flow volume and velocity across it [72,135,193,208,209]. The amount of additional water input made available by burning depends on the interception and storage capacity of residual cover. General estimates suggest that the quantity of interception by unburned trees, shrubs, and grasses on rangelands approximates 1 to 2 mm of event rainfall depending on the cover biomass, rainfall intensity and duration, cover moisture content, and the vertical and horizontal arrangements of cover elements [135]. The conversion of interception loss to rainfall arrival at the soil surface is nearly 100 percent where severe burning uniformly consumes vegetation and ground cover. Greater raindrop impact with vegetation and ground cover removal results in increased soil detachment from rainsplash processes [28,30,46,72,126,181,183]. Ground cover removal reduces surface retention of overland flow and promotes concentration of overland flow into high velocity flow paths with ample erosive energy and transport capacity [28,30,72,181,183,193,203–205,210]. The potential overall effect is a decrease in the time to runoff generation and an increase in cumulative runoff and sediment yield over the duration of a storm event. Overall, the degree to which fire affects infiltration and runoff and erosion processes depends on the magnitude of changes to vegetation, ground cover, and soil properties, as well as inherent site attributes, such as soil erodibility, slope angle, and topography [72,193,209]. For snow-dominated environments, burning of vegetation may alter snow accumulation, the timing of streamflow and peak flow within the year, and the amount of snowmelt runoff. Burning may also result in increased surface temperatures and snowmelt rates due to greater incoming solar radiation post-burn. Any fire-induced reduction in vegetation, therefore, potentially reduces snow accumulation and water availability for biological processes and streamflow generation. Reduced snow retention also potentially alters runoff characteristics from summer thunderstorms on water-limited sites by inhibiting vegetation production and ground cover recruitment. Where snow does accumulate, runoff responses to mid-winter rain-on-snow events may be substantial post-fire [135].

Numerous rainfall simulation experiments have been conducted in burned and unburned PJ woodlands throughout the Great Basin to evaluate fire effects on infiltration, runoff, and erosion (Table 2; [28,30,46,51,126,127,168]). Roundy et al. ([168], Table 2) quantified infiltration and erosion immediately after and 1 year after burning on a singleleaf pinyon-Utah juniper site in the Great Basin. Rainfall was applied to ~0.84 m^2 plots at 83.8 mm h^{-1} for 1 h for dry and wet soil conditions. Infiltration the first year post-fire was similar across burned (72–82 mm h^{-1}) and unburned (78–83 mm h^{-1}) shrub and tree canopy areas for the dry soil conditions, but was lower in burned shrub plots (57–68 mm h^{-1}) than burned tree plots (66–78 mm h^{-1}) for the wet soil conditions. Interspaces generated the lowest infiltration rates and burned interspaces (23–39 mm h^{-1}) had substantially lower infiltration relative to burned shrub and tree canopy areas (67–68 mm h^{-1}) for wet soil conditions. In a multi-site study of burned snow-dominated PJ woodlands in the Great Basin, Pierson et al. [46,126] and Williams et al. [28] applied rainfall on 0.5 m^2 plots at 64 mm h^{-1} for 45 min on dry soil conditions and 102 mm h^{-1} for 45 min on wet soil conditions. In those studies (Table 2), fire had varying impacts on infiltration and runoff, with the main impact being reduced infiltration and amplified runoff from burned relative to unburned tree canopy areas at two of three study sites. Soils were water repellent on burned and unburned tree plots, but litter on unburned plots mitigated repellency effects on runoff. Burning had limited impact on sediment yield from a singleleaf pinyon-Utah juniper site, but increased sediment yield by three- to seven-fold for shrub and tree canopy areas at a Utah juniper site [126]. For a western juniper woodland, burning increased sediment yield for wet soil conditions by 34-fold for tree canopy areas, 24-fold for shrub canopy areas, and 4-fold for interspace plots [28,46]. Overall, burning created more uniform conditions at the fine spatial scale, resulting in greater amounts of runoff and/or sediment for transport to coarser scales 1 year post-fire [28,46,126]. Pierson et al. ([127], Table 2) applied the same rainfall rates to 13 m^2 plots on the same sites as in the Pierson et al. [126] study one year post-fire. High pre-fire runoff levels and sediment yield at the coarser scale persisted in intercanopy areas post-fire at the singleleaf pinyon-Utah juniper site, and runoff and sediment yield were largely unaffected by burning in tree canopy areas at that site. In contrast, runoff and sediment yield increased dramatically (~8-fold and ~30-fold, respectively) after burning tree plots and remained high in intercanopy areas at the Utah juniper site. In the Pierson et al. [46] and Williams et al. [28] studies, high levels of intercanopy runoff and sediment yield for the western juniper woodland persisted 1 year after post-fire and the fire increased runoff and sediment yield by 4–9-fold and more than 20-fold, respectively, in tree canopy areas. Rainfall simulation methods and plot size in those studies were consistent with those in the Pierson et al. [127] study. The studies by Pierson et al. [46,127] and Williams et al. [28] attribute increases in post-fire runoff and erosion following burning to accumulation of runoff and sediment sources from fine scales into high velocity concentrated overland flow over coarser scales. Burning in the studies created more homogeneous bare conditions at all three sites, and the variation in hydrologic and erosion responses across sites post-fire reflects differences in initial vegetation, ground surface conditions, and soil type across the three sites. Studies by Williams et al. [51] and Nouwakpo et al. [211] repeated the experiments of Pierson et al. [127] 9 year after fire. Williams et al. ([51], Figure 4) measured increases in herbaceous cover within the intercanopy on the 0.5 m^2 plots 9 year post-fire than enhanced infiltration and reduced runoff and sediment yield from interspaces by more than two-fold. At the coarser scale, 13 m^2 plots, Nouwakpo et al. [211] measured 3–7-fold reductions of intercanopy runoff and 3- to more than 75-fold reductions of intercanopy sediment yield for the highest intensity storm at the sites. Those studies indicate that herbaceous cover recruitment post-fire enhanced intercanopy infiltration and limited runoff and sediment transport to the hillslope scale. Collectively, the rainfall simulations discussed here demonstrate that fire can impart an initial increase in runoff and sediment yield on PJ woodlands depending on initial vegetation and soil attributes, and that, where burning enhances herbaceous cover, improved infiltration and reduced runoff and erosion at the plot to hillslope scales are likely over time [51,211].

Estimates in the literature are limited for fire-induced increases in soil water availability and streamflow on PJ woodlands. In a multi-site study from the Great Basin, Roundy et al. [42] found that prescribed burning and mechanical tree removal treatments in PJ woodlands increased spring season available soil water by up to 26 day, 20 day, 15 day, and 19 day in the 1st, 2nd, 3rd, and 4th year after treatment, respectively, but the additional time that water was available each spring post-treatment declined as plant cover increased. The precipitation regime was snow-dominated for most sites in the study. Seyfried and Wilcox [212] suggested that woody plant removal by burning can increase deep soil water, but only where soils are deep enough to store surplus water at depth. At the watershed scale, peak discharge rather than cumulative runoff tends to be greater post-fire, and is most pronounced after short-duration, high-intensity, convective thunderstorms over large expanses of severely burned landscapes [209]. Studies from mountainous forest settings indicate hillslope erosion can approach 50–90 Mg ha^{-1} $year^{-1}$ the first few years post-fire, and recovery to pre-fire erosion rates can take 4–7 year [213–215]. Such estimates are limited regarding fire impacts on watershed-scale runoff and sediment yield from PJ woodlands for all regions. Debris flows are uncommon for PJ woodlands following burning, but these events and associated damage to resources, infrastructure, and human life have been documented in the literature on the first few years post-fire [72,216,217].

3.2. Impacts of Mechanical Tree Removal

In contrast to fire, mechanical tree removal treatments retain much of the existing understory vegetation and therefore typically pose few negative impacts on hydrology and erosion processes [31,41,42,133,138]. Numerous studies spanning the Great Basin and Colorado Plateau have evaluated the effects of mechanical treatments on hillslope runoff and erosion processes (Table 2; [45,46,121,127,132,133,172,218]). At the fine spatial scale, Cline et al. [172] and Pierson et al. [126] found that placing shredded tree debris and mulch on 0.5 m^2 interspace plots in a Great Basin woodland enhanced infiltration and reduced runoff and erosion from high intensity rainfall (64 mm h^{-1} and 102 mm h^{-1}, 45 min durations). Sediment yield during application of the highest intensity on mulch covered interspaces was approximately five-fold less than from mulch-free interspaces [126]. Cline et al. [172] found that mulch residue reduced sediment yield from the same simulated storm by eight-fold for bare interspaces and by nearly two-fold for grass interspaces. Pierson et al. [46,127] found that cutting and placing downed trees in the intercanopy had no immediate effect on runoff and erosion rates at multiple PJ woodlands in the Great Basin. In those studies, runoff flowed through downed trees where there were voids in contact of tree debris with the ground surface. In a follow-up study of the sites, Williams et al. [133] found that runoff and erosion from concentrated overland flow were greatly reduced by downed trees 9 year after cutting. The downed trees 9 year post-treatment had settled into place and were in good contact with the soil surface. Downed trees and debris detained overland flow during concentrated flow experiments and allowed more time for water to infiltrate and for sediment deposition [133]. Pierson et al. [45] found that intercanopy runoff and erosion from rainfall simulations (55 mm h^{-1} intensity, 60 min duration, 32.5 m^2 plots) in a cut western juniper woodland in the Great Basin were substantially less than in an adjacent uncut control woodland 10 year post-cutting. The authors concluded that increased herbaceous cover 10 year after cutting improved infiltration and limited concentrated overland flow formation within the intercanopy. Roundy et al. [132] compared runoff and sediment from natural rainfall events on intercanopy plots (10 m^2) in chained-and-seeded and untreated areas of a pinyon-juniper woodland in the Great Basin over a 5-year period. The site commonly received rainfall from high intensity summer monsoonal thunderstorm events. Chaining-and-seeding increased vegetation and reduced bare ground by three-fold relative to the untreated control. The authors determined that chaining-and-seeding reduced runoff and sediment by 5–10-fold as averaged over the 5-year study. Hastings et al. [121] found that cutting pinyon and juniper and evenly distributing tree debris within the intercanopy reduced erosion from high intensity rain events on a degraded and rapidly eroding twoneedle pinyon-oneseed juniper woodland in the Colorado Plateau. Erosion from natural rainfall events over two rainy seasons was one to three orders of magnitude more for untreated than treated micro-watersheds (300–1100 m^2 area). Hastings et al. [121] attributed the reduced erosion after tree cutting to enhanced infiltration and soil water retention afforded by slash, herbaceous cover recruitment, and reduced interconnectivity of runoff and sediment source areas. Jacobs [218] evaluated cover, runoff, and erosion responses to the treatments at the Hastings et al. [121] study sites over a 16-year period post-treatment. During that time, the sites underwent a multi-year drought, wildfire, and a beetle outbreak [218]. Jacobs [218] found that treated areas more rapidly revegetated and improved in hydrologic function relative to untreated control areas following the disturbances and therefore concluded that the treated areas exhibited greater resilience to perturbations than the untreated areas. Collectively, these field studies demonstrate that mechanical tree-removal treatments can effectively enhance infiltration and reduce hillslope runoff and sediment yield the first few years after treatment and over time where the treatments improve vegetation and ground cover and reduce bare ground.

Plot scale experiments regarding tree reduction effects on soil water have largely been confined to the Great Basin. Tree cutting at a western juniper woodland in the Great Basin increased soil water availability at 0–20 cm and 20–40 cm soil depths in each year of a 2-year study and the greater soil water availability in the cut versus uncut areas resulted in greater total plant biomass [38]. The precipitation regime at that site is snow-dominated. Roundy et al. [42] found pinyon and juniper removal increased the number of wet days up to 26 day when applied to PJ woodlands with high tree cover and that soil water was available 8.6 day and 18 day longer in treated versus untreated areas the 4th year after treatment where tree removal was applied at moderate to high tree cover. The additional time that water was available each year post-treatment decreased as understory plant cover increased. Increases in the number of wet days were similar for mechanical and prescribed fire treatments in that study of 13 woodland-encroached sagebrush sites in the Great Basin [42]. Mollnau et al. [163] assessed soil water depletion over a 2-year period for a western juniper site (Great Basin) on plots 20 m $\times$ 20 m and spanning a range of cover conditions resulting from vegetation manipulations, including juniper removal. Spring-season soil water content (mm of water) over 0–60 cm depth on juniper-dominated plots with a shrub and herbaceous understory (106 mm) was less than that measured on mainly bare plots (154 mm) and plots dominated by shrubs and herbaceous vegetation with trees removed (135 mm). Spring season soil water content over the same depths was similar for juniper-dominated plots without a shrub and herbaceous understory (114 mm) in comparison with the shrub- and herbaceous-dominated plots in which trees were removed. Over depths of 60 cm to 90 cm, spring season soil water content was lower for plots with juniper cover (65 mm) relative to plots without juniper cover (90 mm). Soil water content over 0–60 cm depth by the fall season was similar for juniper plots (67 mm) and shrub and herbaceous covered plots (82 mm), and was highest for the primarily bare plots (138 mm). Mollnau et al. [163] attributed the seasonal differences in soil water contents across cover types to differential use of soil water to meet plant needs on vegetated plots, potentially greater interception loss on juniper plots, and minor evaporative losses from mainly bare plots. Evaporation accounted for soil water depletion only to about 15 cm soil depth [163]. Mollnau et al. [163] concluded that juniper, shrubs, and herbaceous plants all utilized soil water resources in the upper 60 cm of the soil profile, that juniper was the primary user of soil water below this depth, and that juniper water use limited deep soil recharge and seasonal soil water carry over. However, a lack of differences in fall season soil water across the juniper-dominated versus shrub- and herbaceous-dominated plots suggests that available soil water is readily used by whatever vegetation occupies a respective site. This is similar to the Roundy et al. [42] study in which increases in the number of wet days declined over time after tree removal as the understory responded to available soil water.

Studies of the effectiveness of mechanical tree removal treatments to increase watershed streamflow have yielded mixed results across the western US PJ domain. DeBoodt ([56], Table 1) determined that tree cutting in a western juniper woodland within the Great Basin initially reduced overall water use for transpiration during the cool season and allowed soil water to increase over the year, resulting in higher end-of-year deep soil water content in cut versus uncut juniper woodlands. Tree cutting had an initial favorable effect on ground water levels and springflow, but treatment effects on streamflow were difficult to discern from variability in precipitation input over the 2 year post-treatment. Ochoa et al. ([57], Table 1) studied the cut and uncut watersheds from the DeBoodt [56] study 13 year after cutting. The authors found that the timing and amount of precipitation strongly affected soil water recharge and that increased soil water recharge during snowmelt led to a rapid water table rise and streamflow. That study detected 1.5- and 1.7-fold greater peak streamflow and springflow rates in the cut versus uncut watershed and annual streamflow was 3.6 times greater for the cut than treated watershed over the 4-year study period. However, annual streamflow and springflow prior to the treatments were on average 1.8 and 3 times greater for the watershed subsequently cut in comparison with the control watershed. The authors did not explicitly state that interception loss affected soil water recharge, but suggested that up to 46% of annual precipitation was intercepted. Niemeyer et al. ([58], Table 1) and Kormos et al. ([59], Table 1) suggested through modeling that juniper dominance on mid-elevation snow-dominated sagebrush rangelands in the Great Basin can alter the amount of snow accumulation and snow distribution across a watershed and thereby affect the spatial distribution, timing and delivery of water availability for soil water recharge and streamflow (e.g., [195,196,198]). The DeBoodt [56], Ochoa et al. [57], and Kormos et al. [59] studies were of Great Basin sites in which precipitation occurs primarily as snow or mixed snow and rain, and streamflow occurs mostly as cool season runoff. Wilcox [190] summarized results from numerous mechanical tree removal studies aimed at increasing streamflow from southern Colorado Plateau and southwestern US PJ woodlands and found that results varied substantially with runoff regime, summer thunderstorm driven versus dominated by cool season frontal rains, snowmelt, or rain-on-snow water input. The Cibecue Ridge paired watershed study (Table 1) in Arizona found that chaining pinyon and juniper combined with slash burning and seeding increased streamflow the first 2 year post-treatment on a ~40 ha watershed relative to an adjacent control watershed of the same size, but streamflow in the following year declined to below the untreated watershed, presumably due to increased transpiration losses associated with seeded grasses (see [66]). At two watersheds at the Beaver Creek Experimental Watershed in Arizona (Table 1), 100% removal of pinyon and juniper trees had no effect on water yield. However, a third watershed targeted only 83% of juniper with herbicide and this increased annual streamflow 65% for the first 4 year post-treatment and 157% after 8 years [64]. The increase in streamflow translated on an area basis to ~13 mm year^{-1}. However, after 8 years dead trees were removed and post-treatment streamflow returned to pre-treatment levels [65]. This suggests that disturbance from the tree removal treatments reduced infiltration in the other two watersheds and/or removal of canopy cover increased evaporation. Further, it seems plausible that the remaining pinyon trees and dead standing juniper trees continued to modify the near-surface energy balance and reduce evaporation in the third watershed. Results from the study are also consistent with the idea that juniper extracts deeper sources of water that recharge streamflow [56,163]. Limited research on streamflow patterns following large-scale tree die-off in the western US suggest that runoff is unchanged by extensive tree mortality in mixed-phase precipitation climates [18,219]. Overall, the literature suggests that increases in soil water and streamflow associated with mechanical tree removal vary by climate regime across the western expanse in which pinyon and juniper woodlands occur and with climate variability and site-specific attributes that affect hydrologic processes.

3.3. Impacts of Drought

The literature is limited regarding impacts of pinyon and juniper drought-induced mortality on hillslope hydrology and erosion. Prolonged drought at a site in the Jemez Mountains of northern New Mexico in the 1950s promoted a landscape-scale plant community transition from ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) to twoneedle pinyon-oneseed juniper vegetation and thereby affected runoff and erosion processes [24,220]. Fire suppression in the years prior to the study, and dating back to the 1880s, facilitated pinyon and juniper establishment beneath and adjacent to ponderosa pines (*Pinus ponderosa* Lawson and C. Lawson) [220]. Drought-induced beetle infestations in the 1950s contributed to ponderosa pine mortality and allowed drought-tolerant pinyon and juniper to dominate site resources. Herbaceous cover was not evaluated at the site in the 1950s, but researchers suggest that herbaceous cover at the site was likely low then, declined with conversion to a PJ woodland, and approached ~2% at the time of the Allen and Breshears [220] study. Overgrazing and vegetation competition for limited soil water promoted bare ground increases at the site over the mid- to late-1900s, propagating extensive and well-connected bare intercanopy area and amplified erosion [24]. Wilcox et al. [24] estimated from a two-year study that annual runoff at the site accounted for <10% of the annual water budget, but that there was little storage of runoff across the site at the watershed scale. The Allen and Breshears [220] and Wilcox et al. [24] studies do not necessarily indicate that runoff increased after the vegetation type conversion from ponderosa pine to PJ woodland, but amplified erosion at the site as reported by the authors implies runoff may have been elevated in association with the plant community transition. In general, amplified runoff and erosion are likely during high water input events where cover is decreased by disturbance [72,193], but research is limited regarding increased plot- to hillslope-scale runoff and erosion associated with drought.

Recent landscape- to regional-scale die-offs of pinyon and juniper in the western US are attributed to periods of drought and associated limited soil water availability, plant water stress, bark beetle infestations, and reduced tree regeneration [13–15,17,20,21,23,220–222]. Breshears et al. [13] document an extensive regional drought across portions of Arizona, Colorado, New Mexico, and Utah during 2000–2003 that produced 40–80% die off of twoneedle pinyon. Drought-induced water-stressed trees were subsequently infested by bark beetles (*Ips confusus*), causing large scale mortality. The more drought-tolerant oneseed juniper had 2–26% mortality at the same locations [13]. Numerous other studies also indicate pinyon species are more susceptible to water stress-related mortality than juniper [14–16,112,223,224]. Pangle et al. [164] imposed drought on twoneedle pinyon and oneseed juniper in a large-scale experiment from 2007 to 2013. The drought treatments reduced ambient precipitation by approximately 55%. By 2012, mortality was 80% for twoneedle pinyon and 27% for oneseed juniper [164], showing the differential sensitivity of these two species to drought.

Estimates of drought-induced tree reduction impacts on streamflow come mainly from recent regional studies in the Colorado Plateau. Guardiola-Claramonte et al. [18] evaluated streamflow for eight basins over a four-state regional area with recent (in the 2000s) drought-related die-off of pinyon. Streamflow for study basins declined over 5 years after pinyon die-off and only a small portion of the decline was attributed to climate variability [18]. The snowline elevation in these watersheds was above the pinyon die-off, thus differences in snow processes were not a reasonable explanation [18]. Based on literature, the authors imply that streamflow reductions were most likely caused by increased soil water use associated with increases in understory herbaceous vegetation following tree die-off and perhaps increased evaporation from surface soils [18]. A similar study by Biederman et al. [219] evaluated streamflow for eight catchments of the Colorado River that underwent substantial tree die-off associated with bark beetle infestations. Streamflow, evaluated over a decade period after tree die-off, decreased in three study catchments and exhibited no change in the remaining five study catchments. The authors suggested the results reflect increased water use by residual vegetation and possibly increased water losses to snow sublimation and evaporation following tree die-off [219]. The primary tree species in the Biederman et al. [219] study was lodgepole pine (*P. contorta* Douglas ex Loudon).

4. Ecohydrologic and Erosion Responses Across Spatial and Temporal Scales and with Changing Climate

4.1. Plot- to Hillslope-Scale Ecohydrologic and Erosion Responses to Tree Reduction

Plot- to hillslope-scale studies spanning the Great Basin and southern end of the Colorado Plateau clearly indicate the initial impacts of tree reduction by fire and mechanical treatments on ecohydrologic function and erosion in PJ woodlands depend largely on the degree to which the disturbance or treatment alters vegetation and ground cover structure and the initial conditions and inherent site attributes such as soil erodibility [28–30,46,72,121,126,127,172,203]. Runoff and erosion rates along a hillslope in PJ woodlands for a runoff-generating event generally vary from minimal for "resource conserving" sites to substantial for "non-conserving" sites [24,25,27,28,45,166,182,191]. Ample vegetation and ground cover buffer runoff generation and limit soil loss on "resource conserving sites" [166,185]. In contrast, well-connected bare patches (e.g., bare ground >50–60%) on "non-conserving" sites are sources for runoff and sediment that accumulate over increasing spatial scales and contribute to concentrated overland flow (Figure 3b) with high flow velocity, erosive energy, and sediment transport capacity [27–30,45,46]. For sites approaching this latter condition, runoff and erosion are well correlated (e.g., Figure 5) and subtle reductions in the vegetation structure and ground cover can greatly amplify soil loss [24,25,29,72]. Consumption of vegetation and litter by fire potentially homogenizes bare surface conditions on PJ woodlands and can thereby increase overall hillslope hydrologic vulnerability and soil availability [28–30,46,72,193,203,205]. As with most rangeland communities, fire impacts on runoff and erosion in PJ woodlands at the fine and patch scales are generally greater for vegetated or litter covered areas than bare interspace areas with pre-existing high runoff and erosion rates (Table 2; [135]). Soils underneath pinyon and juniper trees are prone to soil water repellency [27,46,168,171,174,175] and fire removal of litter in these locations exacerbates repellency effects on runoff and erosion processes [28,30,72,126,127]. Based on Great Basin studies reviewed, runoff and erosion rates from tree and shrub canopy areas during rainfall on PJ woodlands can increase by factors of 4 to more than 20 at fine spatial scales and by 5 to 30 over the patch to hillslope scales, or may exhibit little to no change depending on the degree to which fire alters surface conditions (Table 2). Runoff rates from bare patches commonly exhibit limited change associated with burning, but erosion increases of two-fold are common for intercanopy areas in PJ woodlands of the Great Basin (Table 2). These studies and those from other rangelands in the Great Basin indicate fire-induced increases in point- to hillslope-scale runoff commonly decline after the first year post-fire and that erosion risk at these scales can remain elevated for 3–5 year post-fire depending on post-fire vegetation and ground cover re-establishment [135,181,183,210]. Vegetation and ground cover re-establishment the first few years post-fire on PJ woodlands is strongly dependent on pre-fire cover conditions, the severity of burning, and weather/climate [31,41,49,50,138]. Fewer studies exist for the Colorado Plateau and southwestern US regarding impacts of fire-induced tree reductions on hillslope runoff and erosion, but plot-scale scale trends in post-fire vegetation recovery and hydrology/erosion from the limited studies in these regions are generally consistent with those from the Great Basin (see [51]). Across all regions, fire typically imparts an initial increase in the risk of plot- to hillslope-scale runoff and erosion, and this risk is amplified with increasing storm intensity and burn severity across the rangeland-to-dry forest continuum [72]. The risk for amplified runoff and erosion is likely highest for sites with a summer rainfall-dominated precipitation regime driven by intense monsoonal thunderstorms [216,217,225]. Studies at plot and hillslope scales across the Great Basin and Colorado Plateau indicate mechanical tree reduction treatments can enhance infiltration and reduce runoff and soil loss where tree debris is scattered into bare patches and is in good contact with the soil surface [121,123,126,172]. Several studies reported no reductions in runoff or erosion in the first few years following mechanical tree removal if there was a limited distribution of tree debris throughout intercanopy bare soil patches [46,127]. As with fire, vegetation responses to mechanical tree reduction are strongly related to pre-treatment conditions and post-treatment weather/climate and, on degraded sites, vegetation can take years to re-establish and affect hydrology and erosion [40,41,50,129]. Based on this review, most of what is known about the short-term impacts of pinyon and juniper removal on hillslope hydrology and erosion comes from the Great Basin and, to a lesser extent, the Colorado Plateau. Infiltration, runoff, and erosion rates from these studies are largely based on rainfall simulation experiments at various spatial scales and across moderate to high rainfall intensities (Table 2). The process and structural/functional relationships discussed here likely hold across our three-region focus area. However, several key areas are under-represented in the literature and are fundamental knowledge gaps: (1) post-fire runoff and erosion rates for high intensity monsoonal-type storms in the PJ woodlands of the southwestern US, (2) estimates of plot- to hillslope-scale post-fire runoff and erosion rates from cold-season processes (such as rain-on-snow) in the Great Basin and Colorado Plateau, and (3) hillslope-scale estimates from natural rainfall events on burned PJ woodlands across all regions.

Drought-induced vegetation changes can have fairly rapid (within several years) and long-lasting impacts on hillslope ecohydrologic function in PJ woodlands [24,25,166,220,221]. Wilcox et al. [24] and Allen and Breshears [220] describe landscape level transformation of vegetation type and structure and hydrologic function for a dry forest site in New Mexico. A rapid (<5 year) drought-induced shift in vegetation from ponderosa pine to a PJ woodland with a sparse understory in the 1950s set a trajectory of high erosion rates and long-term soil loss. High erosion rates at the woodland site were perpetuated by extensive bare ground and intense runoff-generating summer thunderstorm events characteristic to the southern end of the Colorado Plateau [24,166]. Similar relationships, but without drought, have been described for pinyon and juniper encroachment of sagebrush rangelands throughout the Great Basin and Colorado Plateau, whereby encroaching trees outcompete understory species for limited water and bare ground and runoff and erosion increase [1,2,26–30,33,38,41,42,45,173]. Likewise, woody plant encroachment and desertification on warm season grasslands in the southwestern US has caused increased bare ground, amplified runoff rates, and long-term soil loss by water and wind erosion throughout much of this region [186,187,226–232]. Collectively, these transformative changes (e.g., [233]) were set into motion through competition for limited water, although the woody plant increases themselves likely have many casual factors [1,3,8,234]. Runoff and erosion on degraded rangelands and woodlands are commonly well correlated and generally increase where bare soil exceeds 50–60% (Figure 5; [27,28,30,46,51,72,181,183]). Therefore, drought and other disturbances that increase bare ground near or above these levels are likely to increase hillslope runoff and/or soil loss until vegetation and ground cover recover. The studies by Wilcox et al. [24] and Allen and Breshears [220] and desertification accounts from the southwestern US (e.g., [186,228,230,232]) indicate recovery requires patience (not always imminent). These accounts further pose concerns given recent regional drought-induced tree die-off accounts and projections for pinyon and juniper woodlands in southern Colorado Plateau and southwestern US [13–15,20,22,23,53,112,117,120]. PJ woodlands in the Great Basin and northern Colorado Plateau appear less susceptible to drought-induced die-off [3,8]. Our understanding of drought effects on vegetation and ecohydrologic processes in PJ woodlands is still evolving and it is difficult to speculate on drought effects beyond the current understanding of key structural and functional ecohydrologic relations for these systems [25,27–30,134,166,185]. Furthermore, disentangling drought effects of hillslope runoff and erosion processes in PJ woodlands is commonly confounded by co-occurring changes in land use and altered disturbance regimes [24].

The long-term impact of tree reduction on hillslope ecohydrologic function and soil loss likely depends on whether the treatment or disturbance enhances resistance and resilience of understory vegetation [28,29,50,51,132,133,218]. Tree reductions on woodland-encroached sagebrush rangelands in the Great Basin and Colorado Plateau commonly target re-establishment of native shrub and herbaceous understory species to improve ecosystem structure and function [1,29,121,125–127]. Numerous studies from these regions have demonstrated favorable mid- to long-term re-establishment of native understory vegetation and associated ecohydrologic function through tree reductions [42,43,45,50,51,133,138,211,218]. A key component to re-establishing native understory vegetation on woodland-encroached sites in the Great Basin and Colorado Plateau is limiting susceptibility to fire-prone cheatgrass (see [31,50]). Cheatgrass readily invades bare patches on PJ woodlands and can subsequently dominate site resources and potentially increase long-term soil loss through more frequent burning [51,72,193,235]. PJ woodlands at the driest and warmest elevations throughout the Great Basin and Colorado Plateau and those without an intact native understory are less resistant to cheatgrass invasion following tree reduction, particularly after fire [31,41,49,50,130]. Likewise, re-establishment of dominance by a native understory and the associated ecohydrologic function on woodland-encroached sites with tree reduction is most likely on sites with an intact, favorable density of native understory species [28,51,211]. Maintenance of a re-established native understory vegetation structure requires follow up tree-removal as tree cover increases and affects understory vegetation production in the years after the initial disturbance or treatment [1,40,41,129,236,237]. The long-term impacts of tree die-off with drought on hillslope ecohydrologic function and erosion depend on drought impacts on vegetation and ground cover structure but can potentially be mitigated [24,218,220]. Jacobs et al. [218] found that restoration treatments in degraded PJ woodlands of the Colorado Plateau increased resilience of ecohydrologic function during subsequent periods of disturbance, including drought, wildfire, and beetle outbreaks. Overall, knowledge regarding long-term ecohydrologic and erosion impacts of tree reductions on PJ woodlands is strongest for the Great Basin and portions of the Colorado Plateau, mostly associated with targeted restoration treatments, and remains limited for much of the southwestern US.

4.2. Climatic Thresholds for Increased Soil Water Availability and Streamflow

Tree removal can alter shading and solar radiation inputs; directly diminish transpiration and interception; reduce surface roughness, and thereby increase wind speeds; and increase night-time cooling by elevating out-going longwave radiation at night through loss of the warm air trapping effect. The net effect of these opposing processes determines whether more or less water is available [134].

These processes can affect the individual components of the water budget. Increases in soil moisture with pinyon and juniper reduction were found across a range of sites in the Great Basin, spanning a wide variation in elevation, climate and soils [42]. Annual precipitation over the 4-year study period ranged from approximately 125 mm to 490 mm, but was closer to 200–300 mm for some sites. Research sites in the northwest Great Basin were characterized by a Pacific maritime-dominated precipitation regime, with mostly winter rainfall, while the central and eastern sites had a continental climate with less winter precipitation, and highly variable summer precipitation. Despite the low amount of rainfall, increases in the days of available water in the springtime were realized in response to prescribed fire and mechanical tree reduction. This effect persisted for 4 years of measurement post-treatment, though the magnitude decreased over time as understory vegetation increased [41,42]. The study results are consistent with those of Bates et al. [38] for a western juniper woodland in the Great Basin. That study reported increased soil water availability following juniper tree reductions even though annual precipitation was near 250 mm. Other PJ woodland studies in the northern Great Basin have reported greater water input on sites without pinyon and juniper relative to similar sites with the trees, with annual precipitation <400 mm in some cases [56,58,59,163]. There are fewer studies of soil water availability with vegetation manipulation for the PJ woodlands in the southwestern US with a mixed-phase precipitation regime. However, Breshears et al. [151] supports the idea that intercanopy areas in PJ woodlands have more available water than tree canopy areas, primarily due to interception losses in a 400 mm precipitation zone. Taken together, these results indicate that in cold-dominated regions with <400 mm, but >200 mm of annual precipitation, manipulations of tree cover will have effects on individual components of the water budget at the plot-level and stand-level scales. This redistribution of limited water resources may help reestablish grasses and shrubs and thus improve ecohydrologic function [1,41,42,45,51,211]. The precipitation limit for southwestern US PJ woodlands that will produce a change in available water is less certain, but likely is >400 mm due to the increased temperatures associated with a greater fraction of summer rainfall that leads to greater evaporation, and due to the potential presence of C_4 grasses in this region that effectively utilize summer rainfall [3]. Collectively, the studies discussed here [38,42,56–59,151,163] illustrate that the influence of pinyon and juniper on soil water input, depletion, and storage is largely dependent on spatial distribution of cover, but is also a function of landscape position, climate, and soil properties as reviewed through this paper.

At the watershed scale, work has been done to assess the effects of pinyon and juniper reductions on the water budget. Studies include empirical assessments and modelling on evaporation, transpiration, interception, snow ablation (the sum of snow evaporation and sublimation), snow accumulation, and streamflow timing and magnitude (see review by Adams et al. [134]). Annual precipitation is commonly <500 mm in the dryland regions that encompass PJ woodlands and conflicting results have been reported in the literature regarding ecohydrologic impacts of tree removal for sites with annual precipitation below this threshold. Hibbert [238] concluded that in order for water yields to increase with tree reduction at sites with cool-season precipitation regimes, more than 400 mm of annual precipitation is required, and in warm climates this is increased to more than 450 mm. A paired watershed study of Great Basin western juniper woodlands found tree cutting initially (first few years) reduced tree-related water use for transpiration and thereby increased soil water deep in the soil profile [56]. Streamflow 13 year after treatment was greater for the cut than an adjacent uncut (control) western juniper-dominated watershed, but the treated watershed historically exhibited greater streamflow than the control watershed, hindering quantification of treatment effects [57]. Ochoa et al. [57] suggested that streamflow for the treated watershed was strongly governed by surface water and groundwater connections and that observations of this connectivity following treatment, along with the increased measured flow, indicate favorable tree reduction impacts on streamflow. The increased hydrologic connectivity following juniper cutting facilitated rapid flushing of the treated watershed, however, and seasonal ground water levels declined more rapidly for the treated versus control watershed. Average annual precipitation at the site is 358 mm and mostly occurs as a mix of rain and snow in the cool season [57]. A watershed-scale modelling study at another central Great Basin PJ woodland suggested that removal of trees from a small area (0.5 km^2) in close proximity to a meadow system would not increase streamflow, but would yield desirable increases in seasonal groundwater levels within the meadow [201]. Simulations indicated additional pinyon and juniper removal (reduction from 80% to 20% cover), with subsequent sagebrush establishment, would still increase groundwater in the meadow and would increase streamflow only in years with more than 400 mm of precipitation. Kormos et al. [59] applied 6 years of measured and modelled data to determine that juniper-dominance of four small sagebrush watersheds in southwest Idaho (northern Great Basin) limited accumulation of snow in deep drifts. Kormos et al. [59] found that the more evenly distributed snow cover under the juniper-dominated conditions resulted in earlier spring snowmelt and summer streamflow cessation relative to conditions dominated by sagebrush cover with deep snow drifts. Early summer cessation of streamflow for the juniper-dominated versus sagebrush-dominated conditions could effectively intensify the already dry summer growing season and has negative ramifications for critical wildlife habitat in the sagebrush steppe [239]. Annual precipitation averages 627 mm at the location studied by Kormos et al. [59] and occurs primarily as winter-season snow and cool-season rainfall [59]. The studies discussed here for the Great Basin, dominated by cold- to cool-season precipitation, indicate tree reductions may yield favorable site-level hydrologic-related ecological benefits even where streamflow is unchanged. Variability in results and methodologies across these studies limit definitive determination of tree reduction impacts on streamflow for Great Basin and Colorado Plateau PJ woodlands with cold- to cool-season precipitation regimes. Likewise, the limited hydrologic-related studies of tree reductions in the southern Colorado Plateau and southwestern US have yielded mixed results [66,190]. Both increases and decreases in streamflow have been reported for the first few years to nearly a decade after tree removal at select sites, some with annual precipitation of more than 700 mm [64,65]. In some cases, initial increases have been attributed to on-site disturbances during tree removal [66].

Tree die-off in response to drought and subsequent insect attack have been well-documented for the southern Colorado Plateau in the early 2000s, and these studies indicate pinyon species are more susceptible to water stress-related mortality than juniper across the pinyon and juniper range [14–16,112,223,224]. A study of five watersheds with tree die-off ranging from 2.6% to 20.8% found streamflow was reduced over a 5-year period after die-off [18]. Streamflow reduction was not a consequence of varying weather [18]. The authors provide several possible explanations, including release of understory vegetation [240,241] or increased solar radiation and evaporation in die-off areas [242]. The snowline elevation in these watersheds was above the pinyon die-off, thus differences in snow processes were not a plausible explanation [18]. A study by Biederman et al. [219] on lodgepole pine forests evaluated streamflow for nearly a decade-long period for eight catchments of the Colorado River that underwent greater than 20% die-off due to mountain pine beetle (*Dendroctonus ponderosae*) attack. Streamflow decreased in three study catchments and exhibited no change in the remaining five study catchments. Similar to Guardiola-Claramonte et al. [18], the lack of streamflow increase was attributed to water use by residual vegetation, but was also potentially related to water losses to snow ablation and evaporation in die-off areas [219]. As indicated by Biederman et al. [219], a growing body of literature suggests that changes in snow processes in response to forest mortality can offset the gains in water inputs from reduced interception and transpiration. To date, there is little evidence that drought-related changes to vegetation in pinyon and juniper woodlands significantly affect water availability at the annual time scale, particularly for the rainfall-dominated southwestern US. In the Great Basin and northwestern Colorado Plateau, large-scale die-offs have not been observed and therefore no assessment of the ecohydrological effects can be made for those regions.

4.3. Implications in Wake of a Changing Climate

Climate projections indicate continued increases in air temperature across the Great Basin, while precipitation projections are more uncertain, ranging from an 11% decrease to a 25% increase depending on location [73]. Synthesis of the existing literature indicated that increases in temperature will increase aridity (increases in vapor pressure deficit), decrease the amount of precipitation that is received as snow, and produce earlier snowmelt and streamflow, which may result in more frequent or longer droughts [73]. Projections for the Colorado Plateau and southwestern US are similar to those of the Great Basin [243–245]. Although there is substantial uncertainty in climate projections [246], most indicate changes that could lead to increases in drought-related tree mortality, invasive annual grass species, and wildfires [18,70,115,247]. Drought-induced forest mortality has been partially attributed to current increases in temperature and insect outbreaks [248]. The recent pinyon pine die-off in the southwest US was explicitly linked to "global climate-change-type drought" [13], so it is plausible that even moderate increases in temperature could produce increased forest mortality [18]. An analysis of all forest types in the western US determined that anthropogenic climate change accounts for 55% of the increase in fuel aridity and, on average, nine additional days of high fire potential [249]. Board et al. [250] conducted a recent analysis specific to pinyon and juniper land cover types in the western US for the northern and southern Intermountain and central and southern Rocky Mountain geographic regions. Across all regions, the fire season started earlier and ended later by the end of a 30-year period from 1984 to 2013. Furthermore, over the entire study area, 25th percentile, median, 75th percentile, and maximum fire size increased through time, with the most dramatic increase in the maximum fire size as compared to the 25th, median, and 75th percentile [250]. These large-scale outcomes are difficult to predict with any certainty, but, based on our review, rapid and large changes in PJ woodland structure and understory vegetation associated with altered disturbance regimes and drought present major ecohydrologic and erosion ramifications for management of PJ woodlands in the western US.

5. Summary and Conclusions

We synthesized a substantial body of literature to evaluate the ecohydrologic impacts of pinyon and juniper tree reductions across plot to watershed scales, over short- and long-term periods, and across regional climatic gradients for the western US. We found that the initial ecohydrologic and erosion impacts of tree reduction on PJ woodlands by fire, mechanical tree removal, or drought depend largely on: (1) the degree to which these perturbations alter vegetation and ground cover structure, (2) the initial conditions, and (3) inherent site attributes. Across rain- to snow-dominated climate regimes, plot- to hillslope-scale studies indicate fire commonly imparts an initial increase in risk to runoff-generating events by homogenizing the landscape and increasing the connectivity of bare ground, sediment availability, and runoff and erosion processes. This risk is likely greatest for sites frequently subjected to high intensity summer thunderstorms and the magnitude of risk declines over time with vegetation and ground recovery (often within 5 year). For all regions, the literature suggests that mechanical tree removal treatments can initially enhance infiltration and reduce hillslope runoff and erosion where tree debris is well-distributed into bare intercanopy areas and in good contact with the soil surface. Recent and historic research on drought-induced vegetation shifts have documented transformative shifts in ecohydrologic function that propagate site degradation. These studies highlight the need to identify sites near tipping points or thresholds and to consider potential conservation or restoration practices that increase resilience of woodlands ahead of disturbances such as drought, fire, beetle infestations, invasive weeds, and altered disturbance regimes. A growing body of literature documents successful conservation/restoration tree-reduction treatments on woodland-encroached sagebrush sites in the Great Basin and Colorado Plateau that enhance vegetation structure and improve ecohydrologic function. Improved ecohydrologic function on these landscapes further enhances the vegetation and groundcover structure and improves long-term ecosystem resistance and resilience to invasive plants, community transitions, and disturbances. The literature is inconclusive regarding tree reduction impacts on soil water. However, studies from the Great Basin and Colorado Plateau indicate tree removal can increase soil water availability along a hillslope over a wide range of annual precipitation levels. The additional amount of available soil water after tree removal typically declines in the first few to four years post-treatment. Our synthesis suggests the annual precipitation requirement for such enhancements in available soil water with PJ tree reductions likely ranges from 200–400 mm for the cold-season precipitation regimes in the Great Basin and Colorado Plateau, and, although suggested with great uncertainty, for the southwestern US likely exceeds 400 mm. The literature is inconclusive regarding tree reduction impacts on streamflow. Studies from the Great Basin indicate tree reduction can affect patterns of snow accumulation and melt and thereby influence the timing of streamflow. Other studies from that region suggest tree reductions may have little impact on streamflow, but can increase groundwater levels, at least temporarily. These studies suggest that, even though tree reduction may not increase streamflow, it may enhance other ecosystem services on some sites. Literature on impacts of tree removal treatments to increase streamflow for the southern Colorado Plateau and southwestern US have yielded mixed results and there is no clear indication that tree removal in PJ woodlands on sites with rain-dominated precipitation regimes will yield long-term increases in streamflow. Recent studies of drought-induced tree die-off in woodlands and forests of the Colorado Plateau have reported reductions to no change in streamflow. The studies attribute responses primarily to increased water use by herbaceous vegetation following tree die-off. To date, there is little evidence that drought-related changes to vegetation in PJ woodlands significantly affect water availability at the annual time scale, particularly for the rainfall-dominated southwestern US. In the Great Basin and northwestern Colorado Plateau, large-scale die-offs have not been observed and therefore no assessment of the ecohydrological effects can be made for those regions.

Our synthesis identified key knowledge gaps that limit ability to forecast ecohydrologic impacts of tree reductions occurring across the vast western US. Across all spatial scales, several key areas are under-represented in the literature and limit current understanding, including: (1) post-fire runoff and erosion rates for natural events, particularly for high intensity monsoonal-type storms in PJ woodlands of the southwestern US, and (2) knowledge of and estimates of post-fire runoff and erosion rates from cold-season processes (such as rain-on-snow) in the Great Basin and Colorado Plateau. Knowledge regarding tree reduction impacts on watershed-level soil water availability, groundwater, and streamflow has increased, particularly for the Great Basin, but is still greatly limited due to the few and often contradictory study results. More work is needed across this scale for all regions, for short- and long-term periods. Lastly, our understanding of drought-effects on vegetation and ecohydrologic processes in PJ woodlands is evolving and it is difficult to speculate on drought effects beyond current understanding. Given limitations discussed here, current understanding of key structural and functional ecohydrologic relations for these landscapes provides the best fundamental basis from which to evaluate and predict potential ecohydrologic and erosion responses to tree reductions across spatial and temporal scales and climatic gradients.

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