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**Ecohydrological resilience of sagebrush rangelands following tree encroachment**

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**Abstract**

The expansion and contraction of pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands in the western US is a broadly occurring phenomenon. The sagebrush (*Artemisia* spp.) vegetation type is vulnerable to woodland encroachment and much of the western US sagebrush domain has transitioned to PJ woodlands. These ecological state changes alter plant community structure and function and delivery of ecosystem services. This study applied a set of vegetation, soil, and rainfall simulation experiments over a range of scales (point to hillslope) to evaluate the ecohydrologic and erosion impacts of a shrubland-to-woodland ecological state transition on sagebrush rangelands on coarse-textured soils. The transition shifted the plant community from a fine to coarse structure and increased the connections between bare areas. Declines in shrub and herbaceous covers associated with pinyon and juniper woodland-encroachment increased the connectivity of runoff and sediment sources. Bare patches in the woodland contributed ample runoff and sediment at the fine spatial scale (0.5 m<sup>2</sup>) that facilitated flow paths and erosion over the hillslope scale. Overall, the shrubland-to-woodland transition marked substantive declines in cover and enhanced connectivity of runoff and sediment sources.

**Introduction**

Pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) [PJ] woodlands substantially increased in density and distribution throughout much of the western US after European settlement, and continue to expand into rangeland plant communities due to intensive land use, historic fire exclusion, and atmospheric CO<sub>2</sub> enrichment. The encroachment of sagebrush shrublands by pinyon and juniper is commonly associated with degradation of understory vegetation and groundcover (Miller et al., 2000), impaired hydrologic function

(Williams et al., 2014, 2022), and amplified soil loss (Pierson et al., 2007, 2010; Roundy et al., 2017). The extensive conversion of sagebrush rangelands to PJ woodlands throughout the western US merits a fundamental understanding of key ecological processes regulating these ecosystems. A primary tenant in pinyon and juniper removal to restore sagebrush vegetation is to implement treatments in the early stages of woodland encroachment, while sagebrush and native perennials remain the dominant vegetation (Miller et al., 2014; Roundy et al., 2014). Further, treatment implementation should target sites where specific objectives such as sagebrush and perennial grass retention/recruitment and reduced runoff and erosion risks are plausible. Decisions on implementing sagebrush restoration treatments to reduce pinyon and juniper require baseline data and understanding on the structure and function of these communities across the diverse landscapes in which they occur.

The purpose of this study was to evaluate the ecohydrologic and erosion impacts of shrubland-to-woodland plant community transitions on sagebrush rangelands on coarse-textured soils. The primary objectives were to quantify (1) vegetation and ground cover conditions at the hillslope scale (990 m<sup>2</sup> plots) and (2) vegetation and ground cover, soil properties, runoff rates, and sediment delivery at the fine spatial scale (0.5 m<sup>2</sup> plots) at a site dominated by sagebrush shrubs (Fig. 1a) and at an immediately adjacent site dominated by pinyon and juniper trees (Fig. 1b). The study sites represent different ecological states (sagebrush shrubland and PJ woodland) of the same ecological site.

## **Methods**

### ***Study area and experimental design***

Experiments were conducted at a sagebrush shrubland (Sagebrush Site) and a PJ woodland (Woodland Site) located (~39.8227°N latitude, -114.014°W longitude) at 1850 m elevation approximately 40 km northeast of Kanab, UT, USA. The sites are immediately adjacent to one another on an Upland Loam (Mountain Big Sagebrush) Ecological Site (Site id: R035XY308UT; NRCS, 2024). The sites receive approximately 400 mm of precipitation annually and have an average annual air temperature of 9.9°C. The sites are on S to SE facing aspects with gentle sloping terrain (6-8% slope). Hillslope-scale vegetation and ground cover at each site were measured on three 33 m × 30 m rectangular site characterization plots. Fine-scale plots were randomly located to occur on interspace (areas between shrub and tree canopies), shrub, and tree microsites (Pierson et al., 2010; Williams et al., 2014). Eight interspace and nine shrub fine-scale plots were installed and sampled at the Sagebrush Site. Twelve interspace, six shrub, and six tree fine-scale plots were installed and sampled at the Woodland Site.

### ***Vegetation and ground surface measurements***

Hillslope-scale overstory tree cover and understory vegetation and ground cover at each site were sampled on the aforementioned 990 m<sup>2</sup> site characterization plots using a set of tree measures and line-point intercept methods consistent with hillslope-scale methods in Williams et al. (2020a). Foliar and ground cover on each site characterization plot were recorded for 60 points with 50 cm spacing along each of five line-point transects 30 m in length and spaced 5-8 m apart, for a total of 300 sample points per plot. Foliar cover and ground cover were measured on fine-scale plots using point frame methods described by Williams et al. (2020a). Foliar and ground cover on each fine-scale plot were recorded at 7 points with 10 cm spacing along each of 15 evenly spaced (5 cm apart) transects oriented perpendicular (downslope) to the hillslope contour, for a total of 105 points per plot. Litter depth on each plot was measured to the nearest 1 mm at four evenly spaced points (~15-cm spacing) along the outside edge of each of the two plot borders located perpendicular to the hillslope contour.

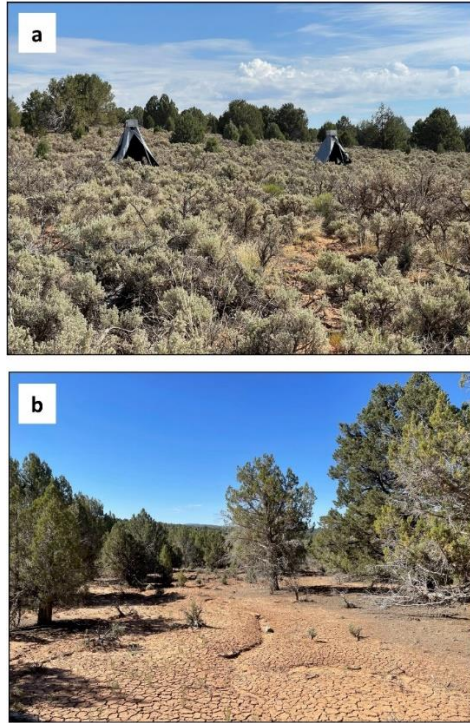


Fig. 1. Photographs of (a) the Sagebrush (*Artemisia* spp.) Site showing rainfall simulators, minimal tree cover, ample understory vegetation, and limited erosion features and (b) the Woodland Site showing an extensive bare intercanopy between tree islands and with visible overland flow paths and erosion features.

### ***Soil characterization and soil property measurements***

Soils for each fine-scale plot were characterized using a suite of sampling methods. Three surface soil grab samples (with litter, duff, and biological soil crust removed) were obtained adjacent to each fine-scale plot and transported to the lab in sealed bags for subsequent soil texture analyses. Soil bulk density was sampled immediately adjacent ( $\approx 15$  cm distance) to each fine-scale plot using a 4.8 cm diameter metal core inserted 5 cm into the soil (litter and duff removed). Bulk density for each soil core sample was calculated in the lab as the oven dried ( $105^{\circ}\text{C}$ ) soil mass divided by the core cylinder volume ( $90.5\text{ cm}^3$ ). The persistence of soil water repellency (SWR) was quantified immediately adjacent to each fine-scale plot under dry antecedent soil moisture conditions using the water drop penetration time (WDPT) test as described by Williams et al. (2020b). Soils were classified as wettable where  $\text{WDPT} < 5$  s, slightly water repellent when WDPT ranged 5 s to 60 s, and strongly water repellent when  $\text{WDPT} > 60$  s.

### ***Rainfall simulations***

Rainfall simulations were conducted to quantify fine-scale runoff and erosion processes using methods and simulators described by Williams et al. (2020a). Two separate, but sequential 45-min rainfall simulation experimental runs were conducted on each fine-scale plot. The Dry Run applied rainfall at an intensity of  $64\text{ mm h}^{-1}$  on dry antecedent soil moisture conditions. The Wet Run applied rainfall at an intensity of  $100\text{ mm h}^{-1}$  on wet soil conditions approximately 15 min following the Dry Run. The mean rainfall intensity and cumulative rainfall applied by run type were similar ( $P > 0.05$ ) across all plots. Actual rainfall applied for 45 min simulations averaged 48 mm and 75 mm for the Dry and Wet Runs, respectively. Timed samples of runoff were collected over 1-min to 5-min intervals throughout each 45-min rainfall simulation and were analyzed in the laboratory for runoff volume and sediment concentration as described by Williams et al. (2020a).

### **Statistical analyses**

Data comparisons for hillslope-scale experiments were conducted using two-sample *t* tests. Assumptions of normality and homogeneity of variance were assessed, and transformations were applied where necessary to address deviances. The Mann-Whitney U test was used for comparisons where transformations were ineffective. Comparisons for fine-scale data were conducted via one-way analysis of variance. Post hoc pairwise comparisons were made using Tukey's honestly significant difference test. Assumptions of normality and homogeneity of variance between groups were assessed and addressed through data transformations. The Kruskal-Wallis method was applied for fine-scale comparisons in cases where normality was not achieved through data transformation. All significant effects were assessed at the  $P < 0.05$  level.

### **Results**

Vegetation cover assessed in summer 2022 quantified the contrasting cover conditions for the two sites. The Sagebrush Site had minimal tree cover (Fig. 1a) and understory foliar cover of 29% shrub, 9% herbaceous (grasses and forbs), and 8% standing dead covers. Litter (45%) and moss (13%) were the dominant ground covers and bare soil was 36%. The Woodland Site had approximately 32% overstory tree canopy cover and about 68% of the area as sparsely-vegetated intercanopy between trees (Fig. 1b). Total understory foliar cover at the Woodland site was 6% and consisted of minor amounts of shrub (2%), grass (1%), and standing dead (2%) covers. Litter cover and bare soil both approached 40%. Most of the litter occurred underneath tree canopies. Incised flow paths and erosion features were common throughout the intercanopy at the Woodland Site (Fig. 1b).

For the fine-scale, shrub microsites at the Sagebrush Site averaged about two-fold greater shrub foliar (64%) cover relative to shrub microsites at the Woodland Site (33%). The ground surface underneath shrubs at the Sagebrush Site was covered by litter (76% cover) and some moss (10%), woody dead debris (5%), and basal plant (4%) covers. The ground surface under shrubs at the Woodland Site had only 41% litter cover and 34% moss and biocrust, 3% woody dead, and 2% basal plant covers. Litter depth averaged 3-5 mm on shrub plots across both sites. Bare soil on shrub microsites averaged 3% at the Sagebrush Site and 19% at the Woodland Site. Interspaces at the Woodland Site had minimal foliar cover, whereas, interspaces at the Sagebrush Site had 9% total foliar cover. At the Sagebrush Site, interspaces were mostly bare (74% bare soil) at the ground surface but had some litter (11%), mosses and biocrusts (10%), woody dead debris (2%), and plant bases (1%). Interspaces at the Woodland Site were also mostly bare (55% bare soil) but had 36% biocrust cover and 7% litter cover. Litter depths were minimal (1-2 mm) in interspaces at both sites. Tree microsites sampled at the Woodland Site had only 4% total foliar cover but were 100% covered by a nearly 50 mm thick accumulation of litter and woody debris.

Soils were generally similar across the study sites, but bulk density and soil water repellency exhibited microsite-specific patterns at each site. Soils across both sites had a loamy sand texture at the surface (0-5 cm depth). Soil bulk density was 1.69-1.73 g m<sup>-3</sup> across all shrub plots and woodland interspace plots, lowest for tree plots at the Woodland Site (1.45 g m<sup>-3</sup>), and highest for interspace plots at the Sagebrush Site (1.99 g m<sup>-3</sup>). The mineral soil surface was strongly water repellent directly under sagebrush canopies at the Sagebrush Site and under tree canopies at the Woodland Site, but soils were wettable in interspaces at both sites.

Table 1. Mean response variables for rainfall simulations (Wet Run, 0.5 m<sup>2</sup> plots) on wet soil conditions at the Sagebrush (*Artemisia* spp.) and Woodland study sites. Means within a row followed by different lowercase letters are significantly different ( $p < 0.05$ ).

	Sagebrush Site		Woodland Site		
	Inter-space	Shrub	Inter-space	Shrub	Tree
<i>Wet Run (100 mm h<sup>-1</sup>, 45 min)</i>					
Antecedent soil moisture (%)	26 a	21 a	26 a	22 a	18 a
Post-simulation soil moisture (%)	33 a	34 a	32 a	34 a	29 a
Mean runoff rate (mm h <sup>-1</sup> )	34 b	5 a	23 b	2 a	19 b
Cumulative runoff (mm)	26 b	4 a	17 b	2 a	15 b
Cumulative sediment (g m <sup>-2</sup> )	104 b	8 a	85 b	10 a	22 ab
Percent of plots with runoff	100%	89%	92%	50%	100%

Few plots generated runoff for the Dry Run overall, therefore rainfall simulation results are restricted to the Wet Run experiments. The Wet Run results showed interspaces as the primary source of runoff and sediment delivery at both sites (Table 1) and that repellency effects persisted even with soil moisture contents approaching 20%. Across the sites, runoff rates and sediment yields were high for interspaces (23-34 mm h<sup>-1</sup>, 85-104 g m<sup>-2</sup>), moderate for tree plots (19 mm h<sup>-1</sup>, 22 g m<sup>-2</sup>), and low for all shrub plots (2-5 mm h<sup>-1</sup>, 8-10 g m<sup>-2</sup>) (Table 1). Runoff rates typically peaked early for water repellent tree and shrub plots and then declined throughout the remainder of rainfall simulation. Litter and moss covers showed variable effectiveness in limiting runoff from water repellent tree and shrub plots.

### Discussion and Conclusions

The preponderance of evidence across spatial scales shows pinyon and juniper encroachment into the sagebrush vegetation type in the study area has altered plant community physiognomy and hydrologic function. The Woodland Site intercanopy (68% of area) was mostly devoid of understory vegetation and the ground surface there was mostly bare or covered by biocrusts (Fig. 1b). Shrub and herbaceous covers were well distributed and bare ground was isolated at the Sagebrush Site (Fig. 1a). For the Sagebrush Site, the fine vegetation structure buffered the effects of high runoff rates and sediment discharge from isolated interspaces and the formation of concentrated overland flow, as evident by limited erosion features at that site (Fig. 1a). At the Woodland Site, extensive sparsely vegetated intercanopy areas facilitated connectivity of runoff and sediment sources from contiguous interspaces (Fig. 1b), as evidenced by the presence of numerous water flow and erosion features (Fig. 1b). Consistent with other woody plant transition studies (Pierson et al., 2007, 2010; Williams et al., 2014; Roundy et al., 2017), our experimental results demonstrate how coarsening of the community structure with sagebrush-to-woodland conversions increases hydrologic vulnerability and soil loss through expanded connections of runoff and sediment sources along hillslopes. This study documents the impacts of PJ woodland encroachment into sagebrush steppe on vegetation cover and hydrologic and erosion processes. Studies documenting vegetation, soils, and hydrologic functioning commonly focus on either the sagebrush ecological state or, more often, the PJ woodland state, with encroachment effects inferred. This study is unique in capturing intact sagebrush state attributes and those

of the PJ woodland state for the same ecological site. The results contribute to conceptualizing and predicting ecological and hydrological responses for similar ecological state transitions in other ecosystems.

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