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Consequences of Piñon-Juniper Woodland Fuel Reduction: Prescribed Fire Increases Soil Erosion While Mastication Does Not

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Abstract

Fire suppression has increased fuel load and the risk of catastrophic wildfire in forest and woodland ecosystems across the Western United States. In an effort to reduce fuel load and restore historical structure and function, land managers have implemented fuel reduction treatments on millions of acres. Reducing fuel loads protects people, structures, and in some cases, improves ecosystem health. However, the ecological risks of soil surface disturbance related to fuel reduction strategies, and subsequent soil erosion, may be significant in some cases. Here, we examined the effects of common fuel reduction strategies (mechanical mastication and two techniques for prescribed burning) on wind and water erosion in two upland piñon-juniper woodlands in SE Utah over 2 years. We also tested the impact of broadcast seeding coupled with fuel reduction as a way to mitigate erosional soil loss. Finally, we analyzed biotic and abiotic predictor variables to evaluate important drivers of soil erosion following fuel treatments. We found that both techniques for prescribed burning—pile burning and broadcast burning—increased wind-related sediment fluxes by an average of 11-fold and 58-fold, respectively. Mastication did not increase wind-related losses over untreated controls. Erosional fluxes measured at silt fences, that captured both wind- and water-driven sediments, followed similar trends with moderate increases from pile burning (fivefold) but larger increases from broadcast burning (17-fold). Seeding did not affect erosion rates. Our results suggest that prescribed fire significantly increases soil erosion in fuel-treated piñon-juniper woodlands and may be a degradation pathway when implementing treatments.

Key words: Piñon-juniper; mechanical mastication; biological soil crusts (biocrusts); erosion; prescribed fire; fuels management; restoration.

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Highlights

- Prescribed burning (both pile burning and broadcast burning) increased soil erosion
- Mastication treatments did not increase soil erosion over controls
- Plant cover and soil stability can be used to manage erosion after fuel reduction

Introduction

Fire suppression and exclusion practices since the early twentieth century have dramatically altered the structure, function, and disturbance regimes of a broad range of forest and woodland types across the western USA (U.S.) (Pyne 2001). Woody infilling and encroachment (Covington and others 1994; Miller and others 2000, 2008; Johnson and Miller 2006; Barger and others 2011; Naito and Cairns 2011), longer fire seasons and larger fires (Westerling and others 2006; Abatzoglou and Williams 2016), increased fire frequency due to human ignitions (Balch and others 2017), and an expansion of the wildland-urban interface (Nowak and Walton 2005; Radeloff and others 2005; Theobald and Romme 2007) all contribute to increased risk of catastrophic wildfires. In response, a broad range of fuel reduction treatments has been applied across millions of acres of western US forest and woodlands (NFP 2000). Common methods of fuel reduction—prescribed fire and mechanical mastication (Agee and Skinner 2005) clearly reduce canopy fuels (Huffman and others 2009; Gottfried and Overby 2011; Young and others 2015). However, these methods also result in significant soil surface disturbance, increasing the risk of soil erosion (Ravi and others 2010). Erosion risk may be particularly high in semi-arid woodlands (Baker and Shinneman 2004) that are characterized by lower plant cover and longer recovery trajectories relative to higher elevation forests (Romme and others 2003). Heightened erosion is of concern because it can accelerate land degradation (Ravi and others 2010).

Plant cover and structure are the major controls over wind erosion (Breshears 2006) in semi-arid woodlands with wind-erodible soils (Breshears and others 2003) common across the Colorado Plateau (Duniway and others 2019). Plant cover offers an important physical barrier to soil movement (Li and others 2007), and perennial bunch grasses are especially effective at capturing eroding windborne soil particles (Munson and others 2011). Fire decreases plant cover, and wind events following both natural and prescribed fires may result in significant wind erosion, with the most severe effects being found in lower elevation shrublands (Sankey and others 2009; Miller and others 2012; Vermeire and others 2005; Field and others 2011). Plant structure, or the height and density of woody and herbaceous plants, determines surface roughness—a key driver of wind processes (Okin and others 2006). When woody plant cover is removed during prescribed fire and mastication, surface roughness decreases, and wind erosion potential increases (Breshears and others 2009).

In addition to plant cover, soil surface stability is another critical control on wind erosion. Biological soil crusts ('biocrusts') represent up to 70% of the biotic groundcover in semi-arid and arid woodlands (Belnap 1990) and are one of the main providers of soil surface stability in certain areas of the western USA (Belnap and others 2009, 2016; Chaudhary and others 2009). Biocrusts are communities of lichens, mosses, cyanobacteria and other microorganisms that form on soil surfaces and they are highly effective in preventing wind erosion (Belnap and Gillette 1998; Leys and Eldridge 1998). However, biocrusts are sensitive to damage by both fire (Zaady and others 2016; Palmer and others 2020) and compressive force (Zaady and others 2016), accompanying mastication treatments. Disturbed biocrusts are known to have friction threshold velocities (the minimum friction threshold to move soil particles) 73%–92% lower than intact biocrusts (Belnap and Gillette 1998), resulting in up to seven times more sediment transport on sandy soils (Leys and Eldridge 1998). Even years after fire and mechanical disturbances to biocrusts, soil stability remains reduced (Ross and others 2012; Root and others 2017), and reduced biocrust cover and biomass can persist for decades (for example, Belnap and Warren 2002).

Similar to wind erosion, plant cover, soil surface stability, and soil topography also act as important controls on water erosion. Vegetation serves as a physical barrier to slow and trap soil and nutrients in overland water flow (Michaelides and others 2009) resulting in lower rates of water erosion in vegetated patches compared to plant interspaces (Reid and others 1999; Schlesinger and others 1999). Prescribed fire reduces plant cover in the short-term, increasing water erosion, particularly on steeper slopes (Wright and others 1976; Pierson and others 2009). Similarly, mastication treatments have increased soil lost to water erosion by exposing bare ground, at least until herbaceous plants recover to protect soil surfaces (Pierson and others

2007). In the interspaces between plants, biocrust microtopography increases surface roughness, slowing water flow to reduce soil erosion (Rodríguez-Caballero and others 2012). Biocrust stabilizes soil (Chamizo and others 2012), protecting soils from the shearing force of water (Rodríguez-Caballero and others 2013). Both fire and compressive forces, such as those resulting from mastication, can damage biocrusts (Johansen 2001; Belnap and Eldridge 2003; Zaady and others 2016), dramatically increasing soil sediment yields (loss) from water erosion compared to intact soils (Chamizo and others 2017; Faist and others 2017).

Our overarching goal in this study was to examine the impacts of fuel reduction on erosion in semi-arid piñon-juniper woodland ecosystems. Piñon-juniper woodlands are the dominant vegetation type across semi-arid regions of the western USA with thousands of acres treated for fuel reduction since the early 2000s (Redmond and others 2014a). Here, we compared the impact of two common fuel reduction treatments—mastication and prescribed fire—on wind and water erosion in upland piñon-juniper woodlands on the Colorado Plateau. We addressed these questions: (1) Do fuel reduction treatments differ in their effects on soil erosion rates? (2) Does seeding mitigate the potential effects of fuel treatments? (3) What plant and soil community characteristics explain erosion after fuel treatments? We hypothesized that prescribed fire would increase rates of soil erosion compared to mechanical mastication due to greater declines in plant and biocrust cover and soil stability after treatment. We hypothesized that seeding would increase post-treatment plant cover, thus mitigating soil erosion.

Methods

Study Area

We experimentally implemented fuel reduction treatments at two sites managed by the BLM on the Colorado Plateau in southeastern Utah: Shay Mesa and Wray Mesa. Both sites are upland shallow loam piñon-juniper sites (NRCS 2004), a common ecological site for the area and representative of vegetation types frequently targeted for fuels reduction treatments in this region. Shay Mesa was chained and seeded in 1959, but experienced rapid recolonization and thickening of the dominant tree species, *Pinus edulis* (two-needle piñon), following treatment. Wray Mesa had never been treated for fuel reduction prior to this experiment. The climate is semi-arid with precipitation occurring bimodally, with monsoonal rains during summer months and snow during winter months. Sites are located on fine sandy loam soils in the Bond-Rizno and Begay series (https://websoilsurvey.sc.egov.usda.gov), and soil classifications were verified on site. Shay Mesa (37°58′42.97″N, 109°31′52.68″W) is at 2237 m, with mean annual precipitation of 396 mm and mean growing season temperature of 14°C. Wray Mesa (38°17′30.75″N, 109°4′20.87″W) is at 2250 m, with mean annual precipitation of 398 mm and mean growing season temperature of 13°C (see Appendix 1: Fig S1). Both sites are relatively flat with slopes below 1% grade.

Dominant tree species at both sites are *Pinus edulis* (two-needle piñon) and *Juniperus osteosperma* (Utah juniper). The shrub layer is dominated by *Artemisia tridentata* (mountain big sagebrush), *Artemisia nova* (black sagebrush), *Ericamerica nauseosa* (rubber rabbitbrush) and *Amelanchier utahensis* (Utah serviceberry). The understory is dominated by *Achnatherum hymenoides* (Indian ricegrass), *Bouteloua gracilis* (blue grama), *Elymus elymoides* (squirreltail), *Poa fendleriana* (muttongrass), *Pedicularis centranthera* (dwarf lousewort), and *Gutierrezia sarothrae* (broom snakeweed).

Experimental Design

We experimentally implemented common fuel reduction treatments (mastication, pile burn, broadcast burn, and untreated control) followed by a seeding treatment (with and without), and measured the effects on wind and water erosion (Figure 1). At each site, we assigned treatments to eight plots of similar size, slope, aspect, soil, and vegetation characteristics. Due to constraints with burning multiple small plots, the two fuel reduction plots at each site were co-located (Figure 1). The seeding treatment was randomly assigned to one of the two plots for each fuel treatment. This resulted in each treatment combination being applied to about 19 ac at Shay Mesa and about 69 ac at Wray Mesa. The eight plots were replicated only once at each site due to time and space constraints of implementing large-scale fuel-reduction treatments. Before treatment, ten 35-m transects were randomly located across each plot to collect all ancillary soil and plant community measures Figure 1). Shay Mesa plots were established in 2009 and Wray Mesa plots were established in 2010.

Mastication Treatment

In the mastication treatment, a wood-mulcher, or ''bullhog,'' mulched trees and the shredded wood was left on the ground. At Shay Mesa, mastication

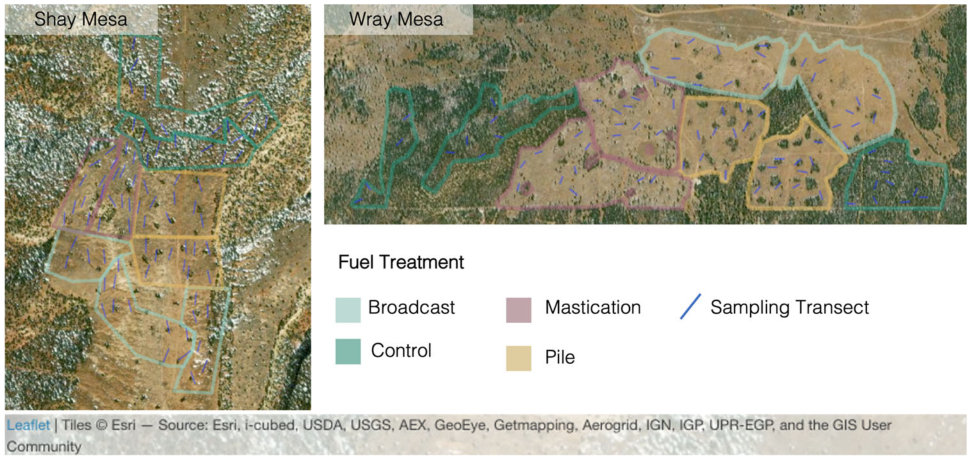

Figure 1. Map of the fuel treatment areas at both sites, with sampling transects. Each polygon is ~ 20 ac at Shay Mesa and ~ 25 ac at Wray Mesa. One of the two treatment polygons at each site was seeded, with the exception of the Broadcast and Pile treatments at Shay Mesa where both polygons were seeded. Data was collected along each transect one and two years after fuel treatments were implemented.

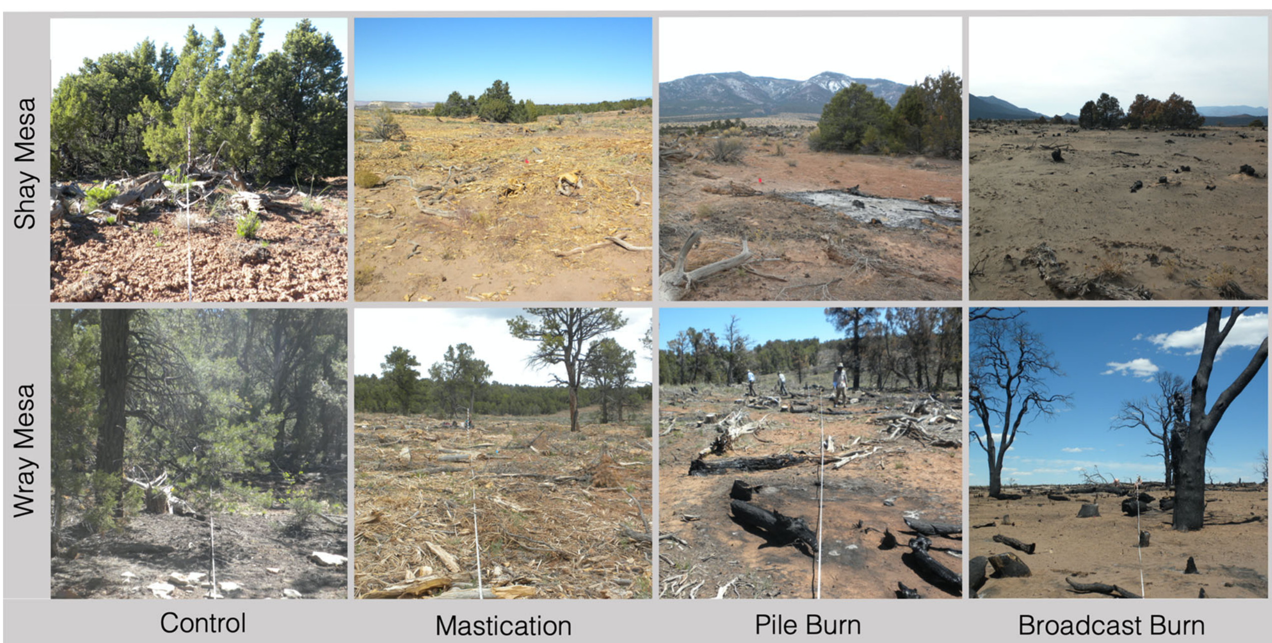

Figure 2. Photos illustrating the effects of fuel reduction treatments on vegetation and soil. Top images show Shay Mesa in the 2009, immediately after treatment implementation. Bottom images show Wray Mesa during the first summer of monitoring, 2011, 4–8 months after treatment implementation.

was implemented across 12 ac in October 2009. At Wray Mesa, the mastication treatment was implemented across 84 ac between November 2010 and January 2011 (Figure 2).

Controlled Burn Treatment

For both of the controlled burn treatments (pile burn and broadcast burn), trees were cut down by hand. For the pile burn treatment, the resulting slash was hand-gathered into 2 m diameter × 2 m height circular piles, dried over the summer, and then burned in the fall (Figure 2). We treated 18 acres at Shay Mesa and 57 acres at Wray Mesa with the pile burn. For the broadcast burn, the slash was left on the landscape to dry over the summer and then the entire area was burned (Figure 2). For burning treatments, the fire was implemented by BLM fire specialists with drip torch. At Shay Mesa, trees across 22 acres were cut and gathered in June 2009 and burning was implemented in November 2009. At Wray Mesa, trees across 71 acres were cut in July 2010 and burned in October 2010. The pile burn was a severe burn isolated into piles, while the broadcast burn was a moderate severity fire spread out across the entire plot.

Seeding Treatment

At both sites, seeding was applied to half of the plots via all-terrain vehicle seed spreaders. The species and richness in the seed mixes differed between the sites (Appendix S1: Table S1), including six grass species at Wray Mesa and 12 species of grasses, forbs, and shrubs at Shay Mesa. Seeding was done prior to treatment in mastication plots but following treatment in the pile burn and broadcast burn plots. During treatment implementation, a seeding error resulted in seeding all broadcast and pile burn treatments at Shay Mesa rather than half of the treatments as originally planned. Thus, there are no unseeded plots in the broadcast or pile burn treatments at Shay Mesa. Pre-treatment data were collected for both sites, followed by monitoring one- and two-year post-treatment.

Water Erosion Measurements

To capture water-driven soil erosion, we installed small silt fences (n = 120, 15 within each treatment area) immediately after vegetation treatments. Silt fences were made of fine aluminum mesh (0.54-mm openings), with a sediment capture surface of 60 cm × 15 cm and a height of 25 cm (modified from Robichaud and Brown 2002). Silt fences were installed facing upslope, across the most prominent water flow path to capture sediments in runoff. Care was taken to ensure fences were not capturing sediment from neighboring treatments; however, we did observe that silt fences captured some sediments derived from wind transport as well. Trapped sediment was collected at least 4 times per year over a two-year period (Appendix S1: Figure S2). In the laboratory, samples were dried and weighed to determine the total dry mass. Sediment fluxes were calculated as the total mass at collection divided by the number of days in the sample period.

Big Spring Number Eight (BSNE) Sampler Measurements

Eight BSNE dust samplers were installed in each treatment block (n = 32) (Fryrear 1986) to capture wind-driven soil erosion. Each sampler was installed 5 m downslope of the center of a random subset of the 10 transects. The BSNE sampler consists of rectangular boxes with wind vanes so that they rotate with the wind. Each box has a 0.001 m^2 opening that rotates to face the wind, trapping aeolian sediment. Dust samplers were installed on an upright pole at 15 cm above the ground. Sediments were collected quarterly (Appendix S1: Figure S3). Following collection, soils were air-dried, placed in a drying oven at 100C for 24 h, and then weighed. BSNE data are reported as sediment flux per day over the collection period.

Ancillary Soil and Plant Community Measures

Soil peds 2–3 mm thick and 6–8 mm in diameter were collected every 4 m along each transect for a total of 9 from each transect. Soil stability was then measured with a field-based soil aggregate stability test as described in Herrick and others (2005). Stability values range from 1 (no aggregate stability) to 6 (75–100% of the soil aggregate remains intact). A line-point intercept method was used to estimate percent cover of vascular plants and soil surface cover (Herrick and others 2005). Soil surface cover was categorized into six groups: bare soil, rock, lichen, moss, light biocrust or dark biocrust. Biocrusts were differentiated by coloration because crusts darken with age and development, and this pigmentation is correlated with soil stabilization (Belnap and others 2008). We expect dark crusts to contribute more to erosion prevention than light crusts, both of which we expect to stabilize soils more than bare soil (Faist and others 2017). Soil chlorophyll *a* is a good indicator of the presence of photosynthetic potential of biocrusts as well as the level of biocrust development (Yeager and others 2004). We collected soil cores to a 2 cm depth. Samples were air-dried and stored in the dark. In the lab we used a methanol double extraction method as described in Castle and others (2011). Extractions were analyzed on a spectrophotometer (Beckman DU-64).

Statistical Analyses

All statistical analyses were done in R (R Core Development Team 2018, version 3.5.2). For both analyses, sediment fluxes from BSNEs (wind-driven erosion) and silt fences (both wind- and water-driven erosion) were modeled separately.

Effect of Fuel Reduction and Seeding Treatments on Erosion

To estimate the effect of fuel reduction treatment and seeding on soil erosion, we fit mixed effects models using the ''lme4 package (Bates and others 2014) with fuel treatment and seeding as fixed effects. Both sediment flux response variables were calculated as the total weight of sediment collected at each BSNE sampler or silt fence over the two-year study period, divided by the number of days of collection. Response variables were log transformed prior to model fit to meet model assumptions. Transect, fuel treatment, seeding, and site were included as nested random effects to control for non-independence in sediment flux sampling. Years since treatment was also included as a random effect. Post-hoc treatment comparisons were done by comparing the least-squared means using the ''emmeans'' package in R (Lenth and others 2018).

Factors Influencing Erosion

Linear mixed-effects models were fit using the ''lme4'' package in R with the maximum likelihood estimation to examine the factors contributing to sediment flux patterns at silt fences and BSNE samplers. These erosion variables were regressed against 15 abiotic and biotic predictor variables that are known to influence soil erosion (including plant cover broken down by functional group, soil surface cover, soil stability, and chlorophyll *a*). All fixed effects were standardized prior to model fitting and checked for multi-collinearity by calculating the variance inflation factor in the ''car'' package in R (Zuur and others 2010; Fox and Weisberg 2019). Data collection of fixed effects was done once per year in late May or early June. In order to align our response variables with the fixed effects in time, we used one annual late May or early June sample for each response variable. This response variable time point represents the average daily flux for that location over three months prior to sampling. In addition to fixed effects, a nested random effect of transect within fuel treatment, within seeding treatment, within site was included to account for the sampling design (Figure 1). Years since treatment was also included as a random effect.

Model selection was done following a top-down strategy (Zuur and others 2010). The initial model was fit with all 15 covariates, and then likelihood-ratio testing was used to drop the least significant (lowest Akaike Information Criterion) covariate with each subsequent model fit using the ''drop1'' function in R. The best-fitting model for each response variable was chosen as the most parsimonious model that did not differ significantly from the model with the lowest AIC (Appendix 2 Tables S2 & S3). That best-fitting model was then refit with a restricted maximum likelihood to produce coefficient estimates (Appendix 2 Tables S2 & S3).

Results

Effects of Fuel Reduction and Seeding Treatment on Sediment Flux

Both pile burning and broadcast burning increased sediment flux compared to controls. Pile burning increased sediment flux by ~ fourfold at silt fences and ~ ninefold in BSNE samplers, when averaged across seeding treatment (Figure 3). Broadcast burning increased sediment by ~ 17-fold at silt fences and ~ 108-fold in BSNE samplers, averaged across seeding treatment (Figure 3). In contrast, the mastication treatment produced modest increases in sediment flux at silt fences and BSNE samplers compared to controls, but this increase was not significant (Figure 3). The differences between sites explained ~ 57% of the remaining variance in the silt fence model, and ~ 71% of the remaining variance in the BSNE model, with Shay

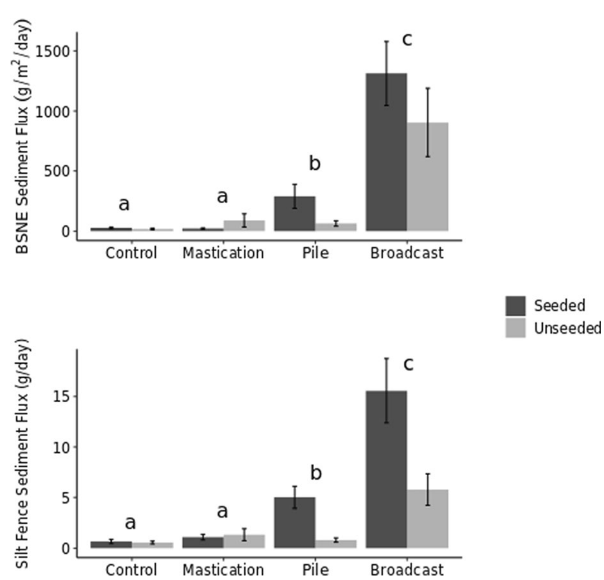

Figure 3. Relationships between fuel reduction treatments and BSNE sediment flux (top) and silt fence sediment flux (bottom). Bars are shaded by seeding treatment, and shown with standard error. Significant differences between fuel treatment least-squared means Tukey's HSD ($\alpha = 0.05$) are indicated by different lowercase letters.

Mesa having higher fluxes than Wray Mesa across all treatments.

There was no significant overall effect of seeding on sediment flux, nor was there a significant interaction between seeding and treatment effects (Figure 3). This result is contrary to the hypothesized relationship that seeded treatments would have decreased sediment flux because of increased understory plant cover. As reported elsewhere, seeded treatments did increase herbaceous cover at Wray Mesa (Redmond and others 2014b) but only increased species richness, not cover, at Shay Mesa (Havrilla and others 2017) (Appendix 1: Figure S4).

Biotic and Abiotic Predictors of Sediment Flux

Among the abiotic and biotic factors predicted to influence soil erosion, tree cover ($\beta = -1.20$ [95% CI, -2.00 to -0.41]), annual forb cover ($\beta = -0.33$ [95% CI, -0.62 to -0.05]), and dark cyanobacterial cover ($\beta = -0.45$ [95% CI, -0.84 to -0.07]) were included as significant predictors of BSNE sediment flux (Appendix S2: Table S2). The higher tree and annual forb cover, and more dark cyanobacteria, were all correlated with decreased sediment captured in the BSNE samplers (Figure 4).

Although vegetation accounted for two of the three significant predictors in the BSNE model, variables related to the soil accounted for the majority of the significant predictors of sediment captured at silt fences. The amount of bare (that is, lacking biocrust or litter) soil cover ($\beta = 0.39$ [95% CI, 0.15–0.63]), annual grass cover ($\beta = -0.22$ [95% CI, -0.41 to -0.02]), and soil chlorophyll *a* content ($\beta = -0.79$ [95% CI, -1.52 to -0.02]) were important predictors of sediment flux in the silt fence model (Appendix 2: Table S3). Annual grass cover and soil chlorophyll *a* were correlated with decreased erosion, whereas incidences of higher bare soil were correlated with increased erosion (Figure 5).

Discussion

Prescribed fire increased soil erosion at these piñon-juniper woodlands during the first two post-treatment years. Our hypothesis that prescribed fire, but not mastication, would increase rates of erosion due to the low plant cover and erosion-susceptible soils at our sites was supported. Mastication treatment did not increase sediment flux over controls, highlighting mechanical removal of fuel as an alternative to prescribed burning when soil erosion is of concern. Seeding did not have a significant effect on sediment flux over the first two years post-treatment, nor did the seeded species cover track precipitation patterns the first two years following treatment ((Redmond and others 2014b); Havrilla and others 2017). The amount of soil mobilized by burning treatments is likely far too great to be controlled by a seeding treatment. Rather than trying to mitigate erosion with seeding, our results point to reducing the level of disturbance caused by fuel reduction treatments. Specifically, managers can use several predictors of soil erosion (that is, bare soil, biocrust cover, herbaceous plant cover, and tree cover) when planning fuel reduction strategies on upland loamy pinon-juniper sites.

Prescribed Burning can Cause Significant Mobilization of Soil

Prescribed burning, both broadcast across the landscape and in piles, increased sediment flux at both sites. The elevated loss and redistribution of soil following prescribed burning is consistent with results reported from the analysis of high-resolution digital imagery for the first year of the study at Shay Mesa (Gillan and others 2016). Gillan and others (2016) measured an average of ~ 139 tons/ha in sediment lost in the first-year post-treatment from the broadcast treatment, with ~ 70 tons/ha in deposition during the same period. Soil stability is an important driver of ecosystem structure and function in drylands (Okin and others 2015), and loss of soil via erosion can trigger long-lasting ecosystem degradation (Suding and others 2004; Okin and others 2009). Although our study did not directly measure nutrient loss associated with sediment flux, other studies have found that significant losses in soil nutrients occur with high sediment loss (Barger and others 2006; Li and others 2007), which can exacerbate a feedback towards desertification. Our burning treatments were correlated with increased bare soil and decreased herbaceous cover and tree cover. The removal of the physical protection conferred by plants is a mechanism for increased sediment fluxes. The greatest sediment fluxes occurred during the first year after treatment, likely before any increases in herbaceous cover from the seeding treatment could provide protection. Further, the broadcast burning treatments resulted in the redistribution of 1000 g of soil per square-meter every day during the first two years post-treatment. That level of erosion likely far exceeds disturbance that can be controlled by seeding.

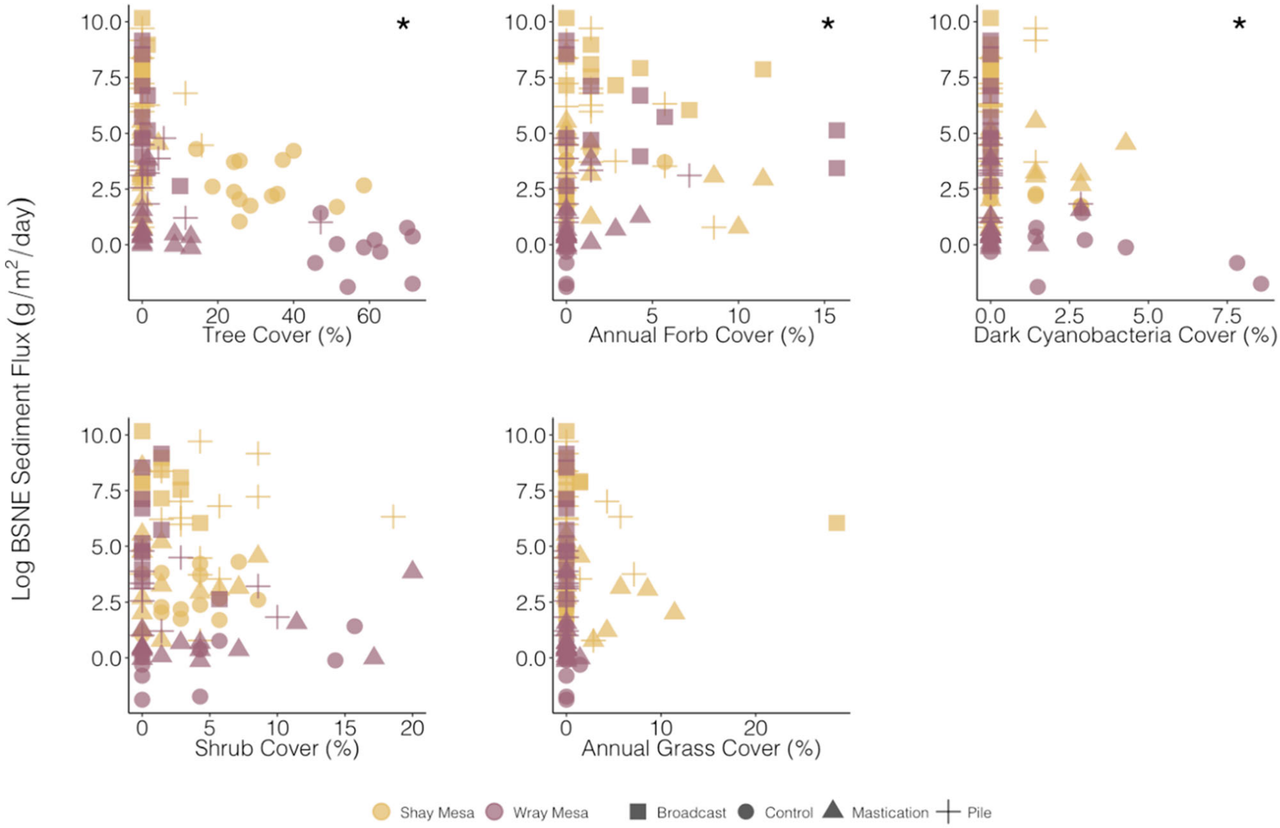

Figure 4. Predictors of wind erosion by fuels reduction treatment. Predictors are on the *x*-axis and wind erosion sediment captured by BSNE samplers 15 cm off the ground is along the *y*-axis on a log scale. All predictors included in the best model are shown, and the significant predictors are highlighted with an asterisk. The log of fluxes from approximately March–May were used in the models.

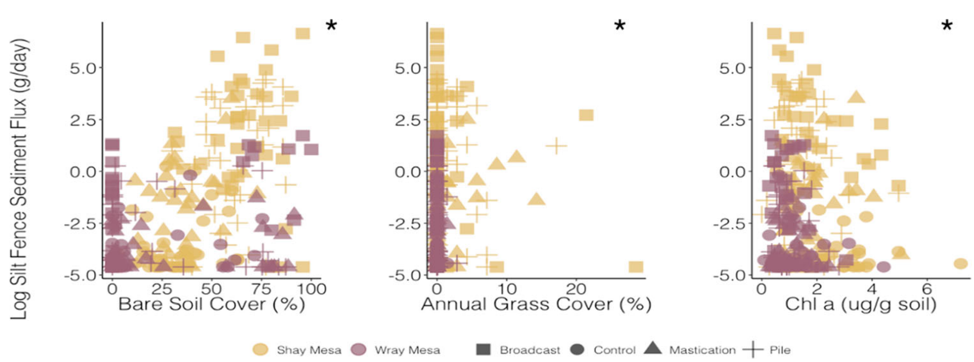

Figure 5. Predictors of silt fence erosion by fuels reduction treatment. Significant predictors are graphed along the *x*-axis and sediment captured in silt fences is on the *y*-axis on a log scale. Chlorophyll *a* is a proxy measurement for the photosynthetic potential of autotrophic soil microorganisms. Fluxes from approximately March–May were used in the predictive models.

Mastication Does Not Increase Sediment Flux

In contrast to prescribed burning, mastication treatments did not significantly increase wind- or water-driven erosion compared to controls. If preventing soil erosion is one of the goals of fuels reduction, mastication should be the preferred treatment over burning, at least for the soil and topographic conditions described. Lower elevation, drier piñon-juniper woodlands have low plant cover with exposed soils in the tree interspaces (Miller and others 2000). It is likely that the woodchips added to the ground by mastication protected exposed soils and increased moisture and nutrient retention—mechanisms that have been recorded in similar studies (Owen and others 2009; Young and others 2013; Roundy and others 2014). Seeding treatments increased herbaceous plant cover at Wray Mesa (Redmond and others 2014b) but not Shay Mesa (Havrilla and others 2017) in the first two years post-treatment, but the disturbance caused by fuel reduction treatment seems to have overwhelmed any protection provided by the recolonizing understory.

Although mastication treatments performed better at lowering sediment flux than fire, there is some evidence suggesting that mastication may make sites more susceptible to plant invasion. Burning treatments can promote invasion by initially decreasing competition, increasing nutrient availability (Blank and others 2007; Condon and others 2011), and increasing soil surface temperatures (Cline and others 2018). However, the mastication treatment uniquely increases water infiltration and available soil water (Owen and others 2009; Roundy and others 2014). Soil–water availability can be a major driver of invasibility in the southwest (Chambers and others 2007), and invasive annuals are capable of rapidly exploiting increases in soil moisture following mastication (Young and others 2013; Redmond and others 2014b; Bybee and others 2016; Havrilla and others 2017), particularly at sites where tree encroachment was severe enough to decrease native perennial cover. Remnant native species can be an important mitigating factor, benefitting from increased soil moisture and reducing establishment of invasives after treatment (Chambers and others 2007). However, remnant vegetation at our site was likely too sparse immediately after treatment to provide significant invasion resistance. Adding native seed to the treatment area in conjunction with mastication has helped to mitigate invasion after fuel treatment in previous studies (Roundy and others 2014), including at our study site (Havrilla and others 2017). Like many piñon-juniper woodlands across the western USA, our study sites contained invasive species including *Bromus tectorum* (cheatgrass) both pre- and post-treatment, however, *B. tectorum* cover increased across all treatments relative to the controls (Havrilla and others 2017). Both native and non-native plant cover often take several years to respond following fuel treatment (Huffman and others 2013; Provencher and Thompson 2014; Havrilla and others 2017) and the short timeframe of our study did not fully capture increases in native species cover, nor in invasion, of the restored community in the longer term.

Plant Cover and Soil Stability Measures to Manage Erosion Risk

Our models included several variables that were significant predictors of sediment flux which can be used to manage soil erosion following fuels treatments. Tree cover, annual forb cover, and dark cyanobacteria cover are significant predictors of BSNE sediment flux. Together, these predictors likely increase surface roughness and trap eroding sediment. Our data show that at tree cover above ~ 5% and annual forb cover above ~ 3% BSNE sediment flux was greatly reduced (Figure 4). Additionally, BSNE fluxes were lower above 5% annual grass cover but the correlation was not significant. There was only one annual forb in the seed mix at Shay Mesa, and neither of the seed mixes contained any annual grasses, so annual establishment was almost entirely independent of seeding. Rather than interpreting these thresholds narrowly by growth form, we suggest that management focus on fuel reduction strategies that maintain both some low level of tree and herbaceous vegetation cover. Herbaceous cover of 15% was found to serve as a wind erosion threshold in one similar study (Hastings and others 2003). A higher threshold of ~ 25% cover has been reported in a lower elevation, drier grassland that did not experience significant soil disturbance from vegetation reduction (Li and others 2007). That study was completed in an area with less vertical vegetation structure, a wider gap size distribution, and on a coarse-textured soil where biological soil crust establishment was minimal. Similar to wind erosion, annual grass cover above 5% significantly reduced silt fence sediment flux, supporting the hypothesis that vegetation, including annual vegetation, is important for intercepting soil particles during overland flow and runoff.

Both sites experienced a vegetation shift from perennial to a higher relative cover of annual species, with implications for erosion. Although annual grasses and forbs provide short-term erosion protection, they are likely not as effective as perennial vegetation at trapping eroding particles and stabilizing soils. At Wray Mesa, annual forbs increased, particularly in the broadcast burns, whereas annual grass cover was higher, and increased post-treatment, at Shay Mesa (Figure S4). Annual grass cover appears to explain a lot of the difference in cover between the controls and the fuel treatments at Shay Mesa, and we know from follow-up work that *B. tectorum* is responsible for much of this increase (Havrilla and others 2017). Fuel treatment that maintains a higher level of remnant perennial cover would likely help to mitigate this shift. Additionally, annual vegetation can increase the occurrence of future natural fire, leading to soil destabilization and increased erosion (Knapp 1996; Pierson and others 2011). It is worth restating that these vegetation predictors of erosion are for the first two years after treatment only, and we know that vegetation can, and in this case did (Havrilla and others 2017) change in the longer term. However, the first two years after fuels treatment, particularly prescribed burning, are critical for preventing large amounts of soil erosion, after which time soils begin to stabilize (Figure S2).

In our system, biocrust is critically important for soil stability (Belnap and others 2009; Chaudhary and others 2009; Belnap and Büdel 2016), which increases under darker, more developed biocrusts (Belnap and others 2008; Chamizo et al. 2012; Pietrasiak and others 2013). Wind-borne sediment flux was negligible when dark cyanobacterial cover was higher than 2%. While all fuel treatments reduced dark cyanobacteria cover, the mastication and pile burn treatments appear to have been less destructive than the broadcast burn (Figure S4). Fire is known to decrease biocrust cover (Palmer and others 2020) and our results indicate that the broadcast burning treatment was intense enough to decrease dark cyanobacteria cover. The pile burn was a more intense burn concentrated into piles, and that appears to have allowed a small amount of dark cyanobacteria to persist, likely outside of the pile burn footprint. Chlorophyll *a*, an indicator of cyanobacteria in biocrust, was also a significant predictor of silt fence sediment flux, and is known to decrease with fire (Ford and Johnson 2006). While managing for chlorophyll *a* is impractical, methods for increasing biocrust cover in disturbed areas, such as by salvaging crust before fuels treatments and then inoculating the soil after treatment, are being developed and could provide a management option to reduce erosion after disturbance (for example, Chiquoine and others 2016).

Bare soil indicates the absence of any biocrust or other protective soil covering such as litter or perennial plant base. Bare soil above 45% was associated with large increases in water erosion, slightly lower than a threshold of 50–70% reported by other studies (Johansen 2001; Pierson and others 2013; Williams and others 2014) (Figure 5). Bare soil differed by site and fuel treatment, with the burning treatments resulting in the most bare soil (Figure S4). Bare soil decreased between the first and second treatment year, markedly at Wray Mesa and modestly at Shay Mesa, as the plant and biocrust communities recovered. These trends track the sediment flux trends observed, where erosion spiked one year after treatment and then decreased by year two, indicated recovery (Figure S2). Ultimately, the high sediment fluxes at silt fences were driven by Shay Mesa, suggesting that a combination of bare soil and low plant cover is particularly catastrophic for soil erosion.

Conclusions and Management Considerations

Our results suggest that fuel reduction techniques involving controlled burning can increase soil erosion on loamy soils in upland pinon-juniper woodland sites on the Colorado Plateau. In many cases, fuel loads have taken decades to 100 + years to accumulate, and controlled burns aiming to maximize fuel elimination can cause hot, long-burning fires that result in erosion with long-lasting consequences for ecosystem health. Mechanical mastication may provide an alternative fuel reduction method that avoids this increased sediment flux. Seeding was not a sufficient management tool to control the soil disturbance and sediment fluxes that resulted from burning. Tree cover, annual forb cover, and annual grass cover were significant predictors of erosion. Management planning for flat, semi-arid woodlands with wind-erodible soils should consider leaving 5% tree cover and at least 10% annual herbaceous cover to help control heightened wind- and water-borne sediment fluxes, and avoid exposing more than 45% of bare soil. Dark cyanobacteria and chlorophyll *a* were soil-specific significant predictors of erosion. Although these factors are more difficult to manage to specific cover thresholds, the importance of soil stability should be kept in mind. Land managers should further consider the dominant erosional processes at the treatment site as well as plant and soil stability management thresholds when planning fuel reduction treatments.

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DATA AVAILABILITY

The URL for the accessible data associated with the manuscript is here: https://doi.org/10.25810/GCHW-MB33.

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