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Ponderosa pine introduction methods following a high-severity stand-replacing fire to promote forest regeneration

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Abstract

Background In July 2012, a lightning strike ignited the Arapaho Fire in the Laramie Mountains of Wyoming and burned approximately 39,700 ha. This high-severity fire resulted in 95% mortality of ponderosa pine (*Pinus ponderosa* P. & C. Lawson) at the University of Wyoming's Rogers Research Site. Ponderosa pine recruitment post-high-severity wildfire is limited in semi-arid and mid-elevation forests in the Rocky Mountain region due to the reduction of seed supplies from living trees, warm temperatures, and limited precipitation. We used an experimental block design to determine management treatments that would increase ponderosa pine abundance, and we measured the impacts to the vegetation community, ground cover, and bare ground following a high-severity wildfire. Treatments included a combination of one pine introduction treatment (natural regeneration, broadcast seeding, and planted seedlings), one logging treatment (no logging, bole only removal, whole tree removal), and erosion control seeding (no erosion seeding and seeding with a native grass mix) in each plot within a block.

Results Our results indicate that the pine introduction treatment "planted seedlings" was the most effective restoration treatment in semi-arid, mid-elevation sites, although the overall survival rate of seedlings from initial planting in 2015 to 2017 was only 6%. "Whole tree removal" had a weak positive effect on the "planted seedlings" ponderosa pine abundance. The estimated mean percent moss cover was higher in the "no logging" treatment, and this treatment resulted in a lower mean percent bare ground. Overall, 2 years after implementation, the management treatments did not result in different vegetation communities.

Conclusions No difference in vegetation functional group cover among the pine introduction and logging treatments at the RRS is likely due to the large landscape heterogeneity with differing slopes and two different aspects coupled with the short time frame since the implementation of the treatments at the site. The direct implications of these findings suggest that hand planting ponderosa pine seedlings is an effective way for managers to reintroduce ponderosa pine 3 years following a high-severity wildfire in semi-arid and mid-elevation sites in the northern Rocky Mountains.

Keywords High-severity, Logging, Ponderosa pine (*Pinus ponderosa*), Post-fire, Restoration, Rocky Mountains, Salvage, Seeding, Seedling

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Resumen

Antedecentes En julio de 2012, un rayo inició el incendio de Arapacho en las montañas de Laramie en Wyoming, EEUU, quemando aproximadamente 39.700 ha. Este incendio de alta severidad resultó en la mortalidad del 95% de los pinos ponderosa (*Pinus ponderosa* P. & C. Lawson) en el sito de investigación Rodgers de la Universidad de Wyoming. El reclutamiento del pino ponderosa luego de un incendio de alta severidad es limitado en bosques de áreas semiáridas de mediana elevación en las montañas rocosas debido a una restricción en la provisión de semillas de árboles vivos, temperaturas templado-cálidas y una limitada precipitación. Usamos un diseño experimental en bloque para determinar el tratamiento de manejo que podría incrementar la abundancia de pino ponderosa y medimos los impactos en la comunidad vegetal, la cobertura de suelo, y suelo desnudo luego de un incendio de alta severidad. Los tratamientos incluyeron una combinación de un tratamiento de introducción de pino (regeneración natural, siembra, y plantación de plántulas), uno de tala (no tala, tala removiendo solo el tronco, y remoción total del árbol), y tratamiento de siembra para control de la erosión (sin siembra y siembra con una mezcla de pastos nativos), todos en parcelas dentro de un bloque.

Resultados Nuestros resultados indican que el tratamiento de introducción de pino mediante la plantación de plántulas fu el método más efectivo de restauración en áreas semiáridas y de elevación media, aunque la tasa general de supervivencia de las plantaciones iniciales de 2015 y 2017 fue de solo el 6%. El tratamiento de remoción total de árboles tuvo un muy débil efecto positivo en la abundancia del tratamiento de plantación de plántulas. El porcentaje medio estimado de la cobertura de musgos fue mayor en el tratamiento de no tala y este tratamiento resultó en el menor porcentaje medio del suelo desnudo. En general, dos años luego de la implementación de los tratamientos, éstos no mostraron diferencias en las comunidades vegetales.

Conclusiones Las escasas o nulas diferencias que se encontraron en los grupos funcionales de cobertura entre los tratamientos de introducción de pino y los tratamientos de tala en el RRS es probablemente debido a la gran heterogeneidad del paisaje, con diferencias en pendientes y dos diferentes orientaciones, acoplados con el escaso tiempo desde la implementación de los tratamientos en el sitio. La importancia directa de la implicancia de estos hallazgos sugiere que la plantación manual de plántulas de pino ponderosa es una forma efectiva, para manejadores de recursos, para reintroducir el pino ponderosa tres años después de un incendio de alta severidad en sitios semiáridos y de mediana elevación en las montañas rocosas de los EEUU.

Background

Wildfires are increasing in frequency and extent because of climate change, fire suppression, and land management (Pausas and Keeley 2021). Mid-elevation forests (e.g., ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forests) in the Rocky Mountains of the western United States (US) are predicted to have the greatest increase in ecological changes and ecosystem succession because of wildfires (Westerling et al 2006; Scasta et al 2016). High-severity wildfires—stand-replacing crown fires that result in 80% or greater tree mortality (including future seed sources)—are responsible for altering the vegetation community in these mid-elevation forests (Kaufmann and Veblen 2006; Hunter et al 2007). Although the understory vegetation community in mid-elevation ponderosa pine forests can become more diverse following a wildfire—with a greater number of native species present and more vegetation cover than before the fire—within 5 years, there may be an increase in invasive plant species (Abella and Fornwalt 2015).

Historically, ponderosa pine forests in the northern Rocky Mountains experienced episodic fires that were typically frequent (with lower elevations experiencing increased fire frequencies) and that burned as either low- or mixed-severity events in late summer and fall (Sherriff and Veblen 2007; McKinney 2019). Mid-elevation forests in the Northern Rockies, including ponderosa pine forests, have shown the largest increases in large wildfire activity, both in frequency and time burning on the landscape (Westerling et al 2006). This is likely due to increased temperatures and an earlier onset of snowmelt (Westerling et al 2006). Increasingly warm and dry conditions after a wildfire and during the growing season may lead to declines in conifer regeneration in ponderosa pine ecosystems (Hankin et al 2019; Kemp et al 2019).

The most indicative predictor of naturally occurring ponderosa pine regeneration after a high-severity wildfire is the distance from living mature ponderosa pines—a maximum distance of 50 m from a seed source is the threshold for abundant ponderosa pine regeneration (Bonnet et al 2005; Haire and McGarigal 2010; Ouzts et al 2015; Chambers et al 2016; Rother and Veblen 2016). Other important factors influencing ponderosa pine germination and regeneration following a high-severity wildfire include summer vapor pressure deficit, soil surface temperature and moisture, and the amount of precipitation that occurs during the growing season (Davis et al. 2019; Korb et al 2019). However, seed source limitation is the real threat to ponderosa pine regeneration, and it is recommended that land managers plant seedlings in high-severity burn patches to accelerate reforestation (Chambers et al 2016).

Microsite enhancement via scattered slash and woody debris from logging can negate post-fire conditions that inhibit seedling establishment and survival (Castro et al 2011) and prevent soil loss from erosion (Moody and Martin 2001; Ouzts et al 2015). Salvage logging is often done to recover the economic loss of trees following a fire; however, the heavy equipment used may cause soil compaction and slow vegetative growth at less productive sites (Wagenbrenner et al 2015; Leverkus et al 2018). Managers may choose to seed with native grass species to reduce both erosion and the spread of invasive species (Morgan et al 2015). Our paper aims to determine (1) the most effective ponderosa pine introduction method at a mid-elevation site in a semi-arid climate and (2) if logging treatments and erosion seeding positively or negatively impact ponderosa pine seedling abundance, vegetation and ground cover, and bare ground. Results from this experiment will aid land managers in the northern Rocky Mountains in determining the best ponderosa pine introduction practices to implement after a high-severity wildfire.

Methods

Site description

The study site is located in southeastern Wyoming at the Rogers Research Site (RRS) (42.236679 N, −105.344440 E) in the North Laramie Mountains (a mountain range that is considered part of the northern Front Range). RRS is managed by the Wyoming Agricultural Experiment Station and owned by the University of Wyoming (UW). The site is approximately 130 ha in size with moderate to steep slopes (5–50%) and elevations that range from 2000 to 2200 m. Mean annual precipitation is 37.6 cm with mean annual temperature ranging between 14°C and less than 0°C.

The Arapaho Fire was started in 2012 by a lightning strike and burned approximately 39,700 ha, killing 95% of the ponderosa pine trees at the RRS. According to Seymour et al. (2017), ponderosa pines covered approximately 80% of the RRS with trees in different age classes. After the Arapaho Fire, approximately 5% of the trees remained, converting a forested landscape to a shrub- and forb-dominated landscape. Understory vegetation associated with ponderosa pine forests in the Laramie Mountains prior to wildfire disturbance were shrubs—primarily in the *Rosaceae* family like antelope bitterbrush (*Purshia tridentata* (Pursh) DC.), chokecherry (*Prunus virginiana* L.), serviceberry (*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.), and Woods' rose (*Rosa woodsia* Lindl.). Forbs included cinquefoil (*Potentilla* spp.), prairie sagewort (*Artemisia frigida* Willd.), geranium (*Geranium* spp.), milkvetch (*Astragalus* spp.), and common yarrow (*Achillea millefolium* L.). The dominant grasses and sedges that occurred were bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve), Idaho fescue (*Festuca idahoenis* Elmer), prairie Junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and Geyer's sedge (*Carex geyeri* Boott) (Howard 2003).

RRS soils are moderately deep (50–100 cm) and coarse textured on hillsides and ridges, where the water table is high, thick, dark, and fine-textured soil occurs. Soil pH ranges from 7.2 in the top 10 cm and 6.4 below 10 cm (Williams and Waggener 2017; Wilkin et al 2019). Soils at the study site are characterized as moderately developed Alfisols and shallow Entisols with low fertility and low water-holding capacity formed from granitic weathering. Alfisols and Entisols are classified as fine-loamy, mixed, superactive, frigid Typic Haplustalfs moderately deep, and loamy-skeletal, mixed, micaceous, frigid Lithic Ustorthents shallow, respectively (Munn et al 2018). The 2012 Arapaho Fire occurred during one of the driest years on record in the state (Scasta 2015). Temperatures for the Arapaho Fire at RRS reportedly ranged from 200 to 500 °C based on black and white soil surface ash color post-fire, ensuring complete consumption of the organic soil horizon in some areas (Wilkin et al 2019).

Study design

An experimental block design was implemented in the summer of 2015 to determine the best combination of management treatments for ponderosa pine restoration following a high-severity wildfire (Herget et al 2018). Four blocks were established at RRS, each block comprising of 18 plots of 50 × 50 m (0.25 ha) in size. Block location was determined based on the feasibility of implementing the treatments and the topographic variability across the site like boulders, dirt roads, steep slopes, and drainages and is not replicated exactly across the landscape (Herget et al 2018).

A full factorial cross of each treatment was applied to each plot within a block with one pine introduction treatment (natural regeneration, broadcast seeding, and planted seedlings) and one logging treatment (no logging, bole only removal, whole tree removal) nested within an erosion control seeding treatment (no erosion seeding and seeding with a native grass species cultivar mix) for a total of 72 plots across all four blocks (Fig. 1). To account for edge effect, all measurements and surveys were conducted in a subplot of 27 × 27 m (0.07 ha) in the center of each plot. From here on, logging treatments "bole only

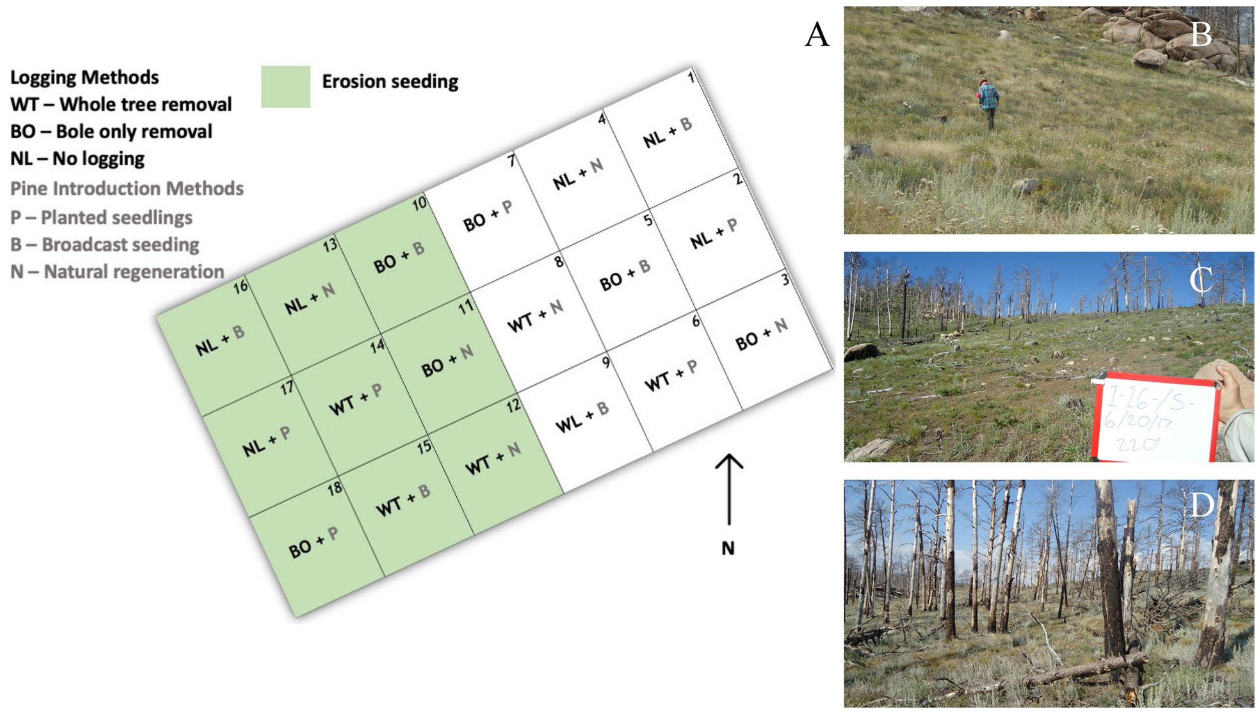

Fig. 1 **A** Example of block (block 3) treatment layout with 18 plots, each 50 × 50 m in size, with corresponding logging treatment, pine introduction treatment, and erosion seeding treatment represented in green, **B** "whole tree removal" logging treatment (WT), **C** "bole only removal" logging treatment (BO), and **D** "no logging" logging treatment (NL) at the Rogers Research Site in the Northern Laramie Mountains, Wyoming. Photo credit: Stephanie Winters

removal" and "whole tree removal" will be referred to as "bole only" and "whole tree".

The pine introduction treatments were randomly assigned to each plot within a block. In total, 2400 one-year-old ponderosa pine seedlings grown in 260-cm^3 tubes were planted in all "planted seedling" pine introduction treatments in 2015. One hundred seedlings were planted per plot. Seedlings were planted in a grid system 3 m apart within the inner subplot. Nursery stock came from Colorado State Forest Service Nursery in Fort Collins, Colorado. Seedlings were hand planted using sharpshooter shovels in block 4 throughout the month of June, block 3 on July 1st–8th, block 1 on July 14th–21st, and block 2 on July 22nd–23rd. Ponderosa pine seeds used in the "broadcast seeding" plots originated from the Roosevelt National Forest in north-central Colorado. Seeds were kept in cold storage and had 70% germination viability. In October 2015, seeds were dispersed using a hand-held broadcast seeder at 158 g per subplot (~4500 seeds). The "natural regeneration" plots were left to naturally regenerate.

Logging treatments were randomly assigned and implemented in the late spring and summer of 2014 and early summer of 2015. Eight plots did not receive random implementation, but logging treatment plots were selected based on the accessibility of the skidder—avoiding steep slopes, boulders, and wet areas. In both the "whole tree" and "bole only" logging treatments, dead ponderosa pine trees were cut with a chainsaw and removed from the plot by a skidder. In the "bole only" removal plots, woody debris larger than 15 cm was removed. All woody debris remaining was evenly distributed across the entire 50 × 50 m plot (Herget et al 2018).

The erosion treatment was not randomly assigned; one-half of each block received the erosion grass seed mix and the other half was left unseeded. Four native grass cultivar species were included in the grass seed mix: "Bromar" mountain bromegrass (*Bromus marginatus* Nees ex Steud.), "Lodorm" green needlegrass (*Nassella viridula* (Trin.) Barkworth), "Pryor" slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners), and "Winchester" Idaho fescue (*Festuca idahoensis* Elmer). Each species had approximately 92% germination viability. The grass seed mix was broadcast seeded using both an ATV and backpack broadcast seeder or evenly by hand (based on ATV access in plots with slash and standing dead trees) in May and June 2015 at approximately 4.7 kg to each 50 × 50 m plot assigned to the erosion treatment (Herget et al 2018). The seed mix was purchased from Western Native Seed in Coaldale, Colorado. The

"Lodorm" green needlegrass seed originated from Montana and the other three species of grass seed originated from Washington.

Seedling surveys

Ponderosa pine seedling surveys were conducted for all pine introduction treatments in the summer of 2017. The "planted seedlings" plots were also surveyed in 2015, 1 to 2 months after seedlings were planted, and in the fall of 2016. Surveys were conducted by walking each subplot in 3×3 m grids, counting all ponderosa pine seedlings, and marking each as live or dead in planted treatments while seedling presence in broadcast-seeded and natural regeneration treatments were counted and marked live. All seedlings were photographed and marked with a Garmin global positioning system (GPS). Seedling numbers per plot were converted to stems ha^{-1} for statistical analysis.

Vegetation surveys

Vegetation surveys were done in June and July of 2017 for all plots. Starting at the northeast corner of each plot, five 0.5-m^2 quadrats were read at 15, 20, 25, 30, and 35 m along a 50-m transect within the subplot. We recorded the percent of bare ground, ground cover (rock, lichen, litter, and woody litter), and both native and invasive plant species canopy cover in each quadrat.

Statistical analyses

We were interested in the mean abundance of ponderosa pine seedlings, mean percent cover of vegetation functional groups, and ground cover among the three pine introduction treatments, the three logging treatments, the two erosion treatments, and the combination of the pine introduction and logging treatments at the RRS. Comparisons of interest were carefully planned and defined before any data were collected; therefore, no adjustments to the multiple comparisons were used. All statistical analyses were done in R version 4.0.3 (R Core Team 2020).

We fit a Bayesian linear mixed-effect model with a negative binomial distribution using ponderosa pine seedling counts as the response variables, pine introduction treatment and logging treatment and their interaction as fixed effects, and block as a random effect using the blme package (Chung et al. 2013) and lme4 package (Bates et al 2015). We also fit a separate model with ponderosa pine seedling counts as the response variables and erosion treatment as a fixed effect and block as a random effect.

We fit a generalized linear mixed-effect model (GLMM) with a Tweedie distribution to estimate differences in the mean vegetation functional group cover and ground cover between pine introduction, logging, and erosion treatments at RRS using the glmmTMB package (Brooks et al., 2017). The mean functional group cover and ground cover were the response variable; pine introduction, logging, and erosion treatments were fixed effects; and block was the random effect.

The model with the lowest AIC score was chosen to determine which fixed effects were most important to include in our model for vegetation functional group cover and ground cover. Erosion control seeding was a fixed effect in models with the highest AIC score; therefore, we removed it from our models. However, to determine if erosion control seeding did affect the mean percent cover of the four grass species in the erosion control seed mix, invasive species, and bare ground, a separate GLMM was fit with the pine introduction treatment, logging treatment, and erosion control seeding treatment as the fixed effects and block as the random factor.

Residuals from the fitted models were graphically checked with the DHARMa package (Hartig 2021) and model assumptions of constant variance and normality were reasonably met. The blocks in the study were assumed to be independent of one another. The estimated marginal means and contrasts for each model were derived using the emmeans package (Lenth et al. 2021). To test for an overall treatment effect, a Wald chi-square test was performed on the chosen models to determine the degrees of evidence against the null hypothesis for the pine introduction treatment, logging treatment, and erosion control seeding treatment.

A permutational multivariate analysis of variance (PERMANOVA) with a Bray-Curtis dissimilarity index was used to determine the effect of logging and pine introduction treatments and erosion seeding on the vegetation functional groups using the adonis function in the vegan package (Oksanen et al. 2022). Permutations were constrained using block. Pairwise comparisons with a Bonferroni correction were done among logging treatments and pine introduction treatments using the pairwise.perm.manova function in the RVAideMemoire package (Hervé 2021).

Results

Ponderosa pine introduction

By August of 2015, the same summer the ponderosa pine seedlings were planted, 1992 out of the 2400 planted seedlings were still alive. This had reduced to 199 the following September of 2016 and only 146 (average of 6.1 ± 7.6 per plot) in summer 2017. This was still much higher compared to 3 seedlings in the "broadcast seeding" (average of 0.1 ± 0.3 per plot) treatment and 9 seedlings in the "natural regeneration" (average of 0.4 ± 1.4 per plot) treatment. The pine introduction treatment (X^2 (2, $N = 72$) $= 58.4$, $p \leq 0.001$) and the logging treatment (X^2 (2, $N = 72$) $= 10.8$, $p = 0.004$) had a separate significant

Table 1 Ponderosa pine estimated means and 95% confidence interval (CI) of stems ha^{-1} for logging treatments and pine introduction treatments for the Rogers Research Site, Northern Laramie Mountains, Wyoming, as measured in summer 2017

Logging treatment[a]	Pine introduction treatment[a]	Estimated stems ha^{-1}	95% CI
No logging	Natural regeneration	41	8, 215
	Broadcast seeding	12	1, 168
	Planted seedlings	772	264, 2252
Bole only	Natural regeneration	16	1, 188
	Broadcast seeding	27	3, 272
	Planted seedlings	1 307	462, 3699
Whole tree	Natural regeneration	215	62, 753
	Broadcast seeding	67	12, 367
	Planted seedlings	2 596	939, 7176

[a] The overall treatment effect was significantly different than the null hypothesis (Pr>ChiSq)

overall treatment effect on the estimated mean ponderosa pine stems ha^{-1}. However, there was no significant interaction between the two treatments (X^2 (4, $N = 72$) = 2.7, $p = 0.7$) (Table 1).

The "planted seedlings" ponderosa pine introduction treatment within the "bole only" and "whole tree" logging treatment had significantly higher estimated means of ponderosa pine seedling stems ha^{-1} compared to the "natural regeneration" and "broadcast seeding" pine introduction treatments within the same logging treatment (Fig. 2). Ponderosa pine estimated mean stems ha^{-1} in the "planted seedlings" pine introduction treatment in combination with the "whole tree" logging treatment (2596 stems ha^{-1} (95% CI 939 to 7176 stems ha^{-1})) was three and a half times greater than the estimated mean stems ha^{-1} in the "planted seedlings" and the "no logging" logging treatment plots (772 stems ha^{-1} (95% CI 264 to 2252 stems ha^{-1})) and almost two times greater than the "planted seedlings" and "bole only" plots (1307 stems ha^{-1} (95% CI 462 to 3699 stems ha^{-1})) (Table 1).

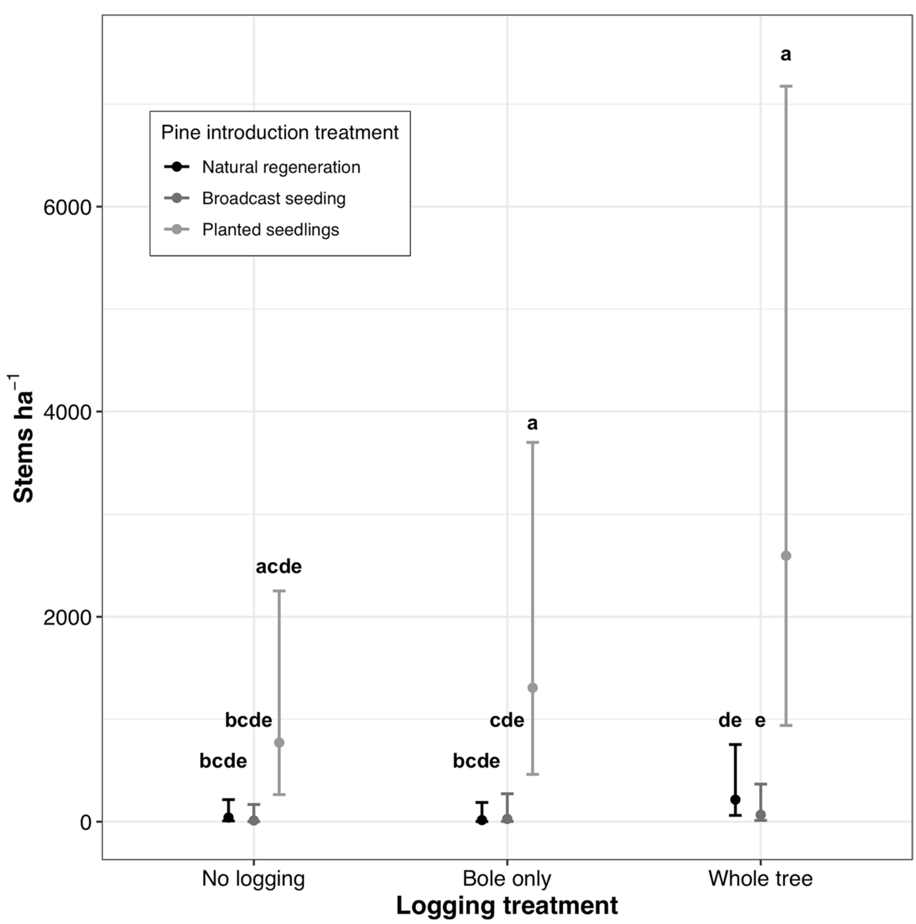

Fig. 2 Ponderosa pine estimated mean stems ha^{-1} and associated 95% confidence intervals for pine introduction method by logging method measured in 2017 at the Rogers Research Site. The letters indicate significant differences among the three different pine introduction treatments combined with the three different logging treatments

The estimated mean ponderosa pine stems ha^{-1} in the "planted seedlings" and "no logging" plots were three times and 12 times greater than the estimated mean stems ha^{-1} in the "natural regeneration" and "whole tree" (215 stems ha^{-1} (95% CI 62 to 753 stems ha^{-1})) and "broadcast seeding" and "whole tree" (67 stems ha^{-1} (95% CI 12 to 367 stems ha^{-1})), respectively (Table 1). However, these contrasts were not significantly different ($p = 0.5$, $p = 0.09$, respectively).

The erosion control treatment had no significant overall treatment effect on the estimated mean of pine seedling stems ha^{-1} (X^2 (1, $N = 72$) = 0.28, $p = 0.6$). Similar findings were observed when focusing solely on the "planted seedlings" pine introduction treatment, where the estimated mean ponderosa pine stems ha^{-1} with erosion control seeding was 1590 stems ha^{-1} (95% CI 468 to 5406 stems ha^{-1}) and with no erosion control seeding 1063 stems ha^{-1} (95% CI 346 to 3267 stems ha^{-1}) ($p = 0.6$).

Vegetation functional groups and ground cover

None of the logging or pine introduction treatments had a significant effect on the percent cover of vegetation functional groups, except for mosses (Table 2). In addition, the PERMANOVA indicated that the overall composition of vegetation functional groups was not affected by any of the logging, pine introduction, or erosion treatments. The three most abundant plant species at the plots were Fendler's ceanothus (*Ceanothus fendleri*), white sagebrush (*Artemisia ludoviciana*), and Geyer's sedge (*Carex geyeri*), of which only the latter species is reported as being present pre-wildfire.

The estimated mean percent moss cover and bare ground were the only response variables measured that showed any change between treatments. Logging treatment had an effect on the estimated mean percent moss cover (X^2 (2, $N = 72$) = 23.1, $p \leq 0.01$), and a marginal overall effect on the estimated mean percent bare ground (X^2 (2, $N = 72$) = 5.73, $p = 0.06$). The estimated mean percent moss cover in the "no logging" treatment was estimated to be 2.7 times higher (95% CI 1.3 to 5.3 higher) and 3.1 times higher (95% CI 1.5 to 2.2 higher) than the "bole only" and "whole tree" logging treatments, respectively (Fig. 3A). Conversely, the estimated mean percent bare ground in the "no logging" logging treatment was estimated to be 9.7 times lower (95% CI 7.6 to 12.3 lower) and 7.7 times lower (95% CI 6 to 9.7 lower) than the "bole only" and "whole tree" logging treatments, respectively (Fig. 3B). Although the estimated mean percent woody cover was not significantly different among the three logging treatments, there was an overall treatment effect of logging treatment (X^2 (2, $N = 72$) = 6.73, $p = 0.03$) (Table 2). The pine introduction treatment had no overall treatment effect on either the estimated mean percent moss cover or bare ground (Table 2). In a separate model, erosion control seeding in addition to the pine introduction and the logging treatments was added as a fixed effect. Erosion control did not have a significant overall treatment effect on the estimated mean percent bare ground (X^2 (2, $N = 72$) = 3.38, $p = 0.06$) compared to the logging treatment (X^2 (2, $N = 72$) = 17.4, $p \leq 0.001$) in this model.

The invasive species encountered at the plots were cheatgrass (*Bromus tectorum* L.), field brome (*Bromus arvensis* L.), and Canada thistle (*Cirsium arvense* (L.) Scop.). The estimated mean percent of all invasive species cover did not significantly differ among logging treatments, pine introduction treatments, or erosion seeding. However, Canada thistle was significantly different between individual logging treatments. The estimated mean percent Canada thistle cover was four and nearly six times greater in the "bole only" logging treatment (2.17 (95% CI 1.04 to 4.51 more)) than the "no logging" (0.5 (95% CI 0.1 to 1.64)) and "whole tree" (0.4 (95% CI 0.12 to 1.30)) logging treatments, respectively.

Only two of the four seeded cultivar grass species from the erosion mix, "Bromar" mountain brome (*Bromus marginatus*) and green needlegrass "Lodrom" (*Nasella viridula*), were identified and recorded during the 2017 survey. In plots with erosion control seeding, the mean percent cover of the sum of the two grass species was estimated to be 1.68 times higher (95% CI 0.41 to 1.62 higher) compared to plots with no erosion control seeding, resulting in an overall erosion treatment effect (X^2 (1, $N = 72$) = 7.81, $p \leq 0.01$).

Discussion

Treatment effect on ponderosa pine seedling survival and regeneration

The pine introduction treatment "planted seedlings" had the most ponderosa pine seedlings. Despite the difference in ponderosa pine seedling numbers among the pine introduction treatments, the total survival for "planted seedlings" treatment 2 years post-planting was only 6.1%. One potential explanation for the low seedling survival may be the timing of the planting, which was May–July. In July, temperatures reached a high of 30 °C and the site received 40 mm of precipitation—harsh growing conditions for acclimating ponderosa pine seedlings (Herget et al 2018). Colorado State Forest Service (CSFS) recommends hand planting seedlings in March, April, or October in Colorado to prevent seedlings from expending resources during the hottest months of the year. Also, rather than planting seedlings in a grid pattern where seedlings are planted at regular intervals—seedlings should be planted either randomly or in random clusters that capitalize on microclimate water availability (Landis

Table 2 Estimated mean percent vegetation functional groups and ground cover, associated 95% confidence interval (CI) and Wald chi-square *p*-value for logging treatments: "no logging," "bole only," and "whole tree" and pine introduction treatments: "natural regeneration," "broadcast seeding," and "planted seedlings" at the Rogers Research Site, Northern Laramie Mountains, Wyoming, as measured in summer 2017

	No logging		Bole only		Whole tree		Logging treatment	Natural regeneration		Broadcast seeding		Planted seedlings		Pine introduction treatment
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Pr > ChiSq[a]	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Pr > ChiSq[a]
Vegetation functional group cover (%)														
Graminoids	17.7	14.6, 21.4	21.3	17.6, 25.8	18.8	15.6, 22.8	0.83	16.0	13.2, 19.4	20.4	16.9, 24.7	21.7	17.9, 26.3	0.34
Forbs	19.6	15.1, 25.4	22.4	17.4, 29	19.4	14.9, 25.1	0.67	18.6	14.3, 24.2	19.4	14.9, 25.2	23.5	18.2, 30.4	0.90
Shrubs	21.6	14.3, 32.7	14.1	9.2, 21.7	19	12.5, 28.9	0.47	18.9	12.4, 28.8	18.5	12.2, 28.2	16.5	10.8, 25.2	0.87
Invasives	2.7	1.1, 6.6	3.7	1.5, 9.1	2.9	1.2, 7.1	0.92	2.5	1.0, 6.3	3.2	1.3, 7.8	3.5	1.4, 8.7	0.74
Mosses	4.0a	1.9, 8.1	1.3b	0.6, 2.8	0.9b	0.4, 2.2	<0.01	1.0	0.4, 2.4	2.1	1.0, 4.4	2.2	1.1, 4.8	0.07
Ground cover (%)														
Bare ground	*9.9a*	7.7, 12.9	*19.6b*	15.3, 25.2	*17.6b*	13.7, 22.6	0.06	15.5	12, 20	17.5	13.6, 22.5	12.7	9.8, 16.5	0.98
Litter	19.3	15.5, 24	20.9	16.9, 26	18.7	15, 23.2	0.52	20.4	16.4, 25.4	18.8	15.1, 23.4	19.6	15.8, 24.4	0.51
Rock	28.2	20.9, 38	21.6	15.8, 29.5	21.1	15.4, 28.9	0.15	24.5	18.1, 33.3	24.6	18.1, 33.3	21.3	15.6, 29.1	0.45
Woody	9.5	7.2, 12.4	11.1	8.6, 14.4	8.5	6.4, 11.3	0.03	9.4	7.2, 12.4	10.0	7.6, 13.1	9.6	7.3, 12.5	0.21

[a] Wald chi-square test

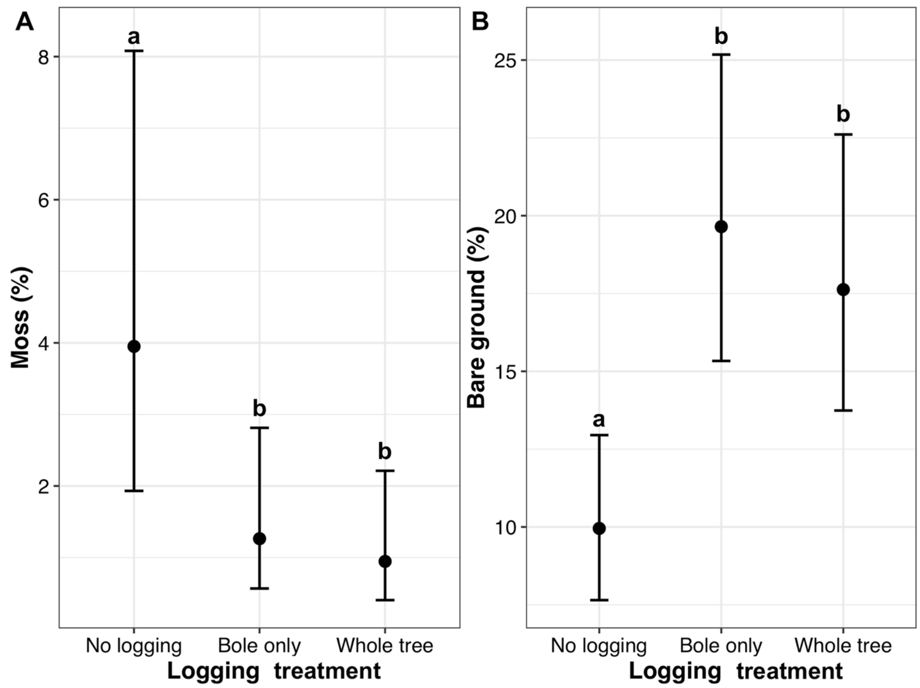

Fig. 3 Estimated mean percent **A** moss cover and **B** bare ground and associated 95% confidence intervals by logging treatment measured in 2017 at the Rogers Research Site. The letters indicate significant differences among the three different logging treatments

and Dumroese 2006; North et al 2019). Stevens-Rumann and Morgan (2019) suggest planting seedlings in cool and wet areas on the landscape and avoiding sites with harsh conditions to improve seedling success.

In addition to low seedling survival rates, there was very low apparent germination or presence of pine seedlings in plots with "broadcast seeding" or "natural regeneration" pine introduction treatments. Low germination rates of ponderosa pine seeds occur from the failure of roots to establish, herbivory, desiccation, and cold temperatures in winters (Stein and Kimberling 2003). Rietveld and Heidmann (1976) compared spot seeding (planting seeds directly into the soil) with broadcast seeding treatments of ponderosa pine post-wildfire and found that spot seeding resulted in higher germination rates (3800 seedlings acre^{-1}) compared to broadcast seeding (300 seedlings acre^{-1}). Conifer regeneration studies have found that natural regeneration of conifers, specifically ponderosa pine trees, is limited with increasing distance from the remaining seed producing ponderosa pines in the area (Bonnet et al 2005; Haire and McGarigal 2010; Chambers et al 2016; Rother and Veblen 2016). For natural regeneration to occur in areas that have experienced a high-severity wildfire, a minimum of 10 years may be required for higher numbers of seedlings to occur if the seed source is over 100 m away, which was the case for most of the RRS restoration plots (Ouzts et al 2015).

There was an overall logging treatment effect on ponderosa pine seedling abundance, with the "whole tree" logging treatment having a higher estimated mean stem ha^{-1} in all three pine introduction treatments. However, planting ponderosa pine seedlings was by far the most effective method at re-introducing seedlings to the landscape 5 years following the Arapaho fire, regardless of logging treatment. Conversely, Ritchie and Knapp (2014) found no significant effect on the survival of planted ponderosa pine seedlings from salvage logging. Studies have also shown that salvage logging post-high-severity wildfire does not increase natural regeneration, because natural regeneration is so dependent upon nearby seed sources (Keyser et al 2008; Morgan et al 2015). Povak et al. (2020) reported that 13–28 years following mixed- and high-severity wildfires in eastern Washington natural regeneration for conifer species was highest at sites that had been salvage logged except for ponderosa pine trees. Their results emphasized that natural regeneration was lowest at sites when seed sources were greater than 68 m away for all conifer species after a high-severity fire independent of logging treatment.

Treatment effect on vegetation and ground cover

Logging post-high-severity wildfire in a semi-arid environment is an additional disturbance to a site. We observed lower percent moss cover and higher percent bare ground in plots where logging had occurred compared to the "no logging" treatment; removal of stems and logs with logging equipment removes microsites for mosses to colonize (Hernández-Hernández et al 2017) and leaves soils exposed to evaporation from solar radiation (Leverkus et al 2021). Little research has been done regarding moss cover, wildfire, and salvage logging, especially in the Rocky Mountain region. More moss cover and less bare ground may indicate microsites on a landscape with higher soil moisture than surrounding areas.

Forbs and shrubs were the vegetation functional groups with the highest estimated mean percent cover at RRS, followed by graminoids and invasive species, but overall, there were no significant differences among logging treatments or pine introduction treatments for these individual vegetation functional groups. Similarly, Keyser et al (2008) found that salvage logging in high-severity burn areas had no effect on the native vegetation understory cover, relative abundance, or the introduction of invasive species.

The percent cover of the most abundant invasive species, Canada thistle (*Cirsium arvense*), was higher in the "bole only" logging treatment and may indicate that Canada thistle was present in those plots prior to the Arapaho Fire. Wright and Tinker (2012) found that after wildfires in Yellowstone National Park, Canada thistle occurred in areas with more fertile soils. However, because of Canada thistle's inability to reshape its environment or compete with native vegetation for resources, Canada thistle disappeared from the system 18 years after its detection, which we may expect to see at our site in the future.

Only two seeded grass species out of the four in the erosion seed mix were able to be identified and recorded in 2017: mountain bromegrass (*Bromus marginatus*) and green needlegrass (*Nassella viridula*). However, it is unknown if these two species were the seeded "Bromar" mountain bromegrass and "Lodorm" green needlegrass variety or if they were grasses that had regenerated after the wildfire. Erosion seeding results were inconclusive despite statistical significance; erosion seeding occurred 3 years post-fire and native perennial grass species present at RRS had already established robust populations requiring the seeded perennial grasses to compete for space and resources. In a meta-analysis of 94 papers, only one out of ten erosion studies found that erosion was reduced post-precipitation events 2 years after seeding following a wildfire (Peppin et al 2010). Also, when native vegetation species are used as an erosion treatment, invasive species diversity or richness did not differ between treatments that were seeded and not seeded (Stella et al 2010), indicating that erosion seeding is not an effective or economical practice.

Conclusion

Planting seedlings is the most effective restoration treatment for introducing ponderosa pine seedlings to a semi-arid, mid-elevation, high-severity burn site within 3 years post-wildfire. Ponderosa pine seedling survival rates were low in the "planted seedling" treatment, but even in the logging treatment with the lowest seedling abundance, "planted seedling" density was still much greater than recorded current and historical densities of ponderosa pine in the northern Front Range based on dendrochronology records (Battaglia et al 2018). Natural regeneration stem ha^{-1} is more within the range with historical ponderosa pine densities in all logging treatments. However, with increasing temperatures, limited precipitation, and increased wildfire frequency in semi-arid environments of the Rocky Mountains, it is advised that to aid in the regeneration of a resilient ponderosa pine forest, land managers should plant seedlings using an ecological lens.

Salvage logging had a weak positive effect on ponderosa pine survival and regeneration 3 years following a high-severity wildfire at the Rogers Research Site. Salvage logging is also considered an initial disturbance after a natural disturbance and negatively impacted moss cover, regardless of slash retention, and increased bare ground in comparison to "no logging." However, salvage logging may be used to achieve other management objectives where ponderosa pine regeneration is not the goal. Regardless of the logging treatment implemented, ponderosa pine seedlings should be planted if reforestation is the main objective 3 years after a high-severity wildfire. Also, erosion seeding did not affect the vegetation functional groups, ground cover, or bare ground at the RRS.

Conifer seedling recruitment after high-severity wildfire may take decades in areas with low seed sources. Continued monitoring of pine seedling recruitment and survival as well as vegetation communities, in combination with soil abiotic and biotic measurement, will indicate the potential rate of recovery of ponderosa pine forests in semi-arid and mid-elevation regions.

Abbreviations

B Broadcast seeding
BO Bole only removal
CSFS Colorado State Forest Service
GLMM Generalized linear mixed-effect model
N Natural regeneration
NL No logging
P Planted seedlings
PERMANOVA Permutational multivariate analysis of variance
RRS Rogers Research Site
US United States
WT Whole tree removal

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Authors' contributions
SW collected and analyzed the data and wrote the manuscript. LVD was the PI, helped collect data, and edited the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
The authors of this manuscript consent to publication.

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The authors declare that they have no competing interests.

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