Ponderosa Pine Introduction Methods Following a Stand Replacing Wildfire in the Laramie Mountains of Wyoming

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Research Article

Keywords: high-severity, logging, ponderosa pine (Pinus ponderosa), post-fire, restoration, Rocky Mountains, salvage, seeding, seedling

Posted Date: March 14th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1397376/v1

Version of Record: A version of this preprint was published at Fire Ecology on January 19th, 2023. See the published version at https://doi.org/10.1186/s42408-022-00152-5.

Abstract

Background

In July 2012, a lightning strike started the Arapaho Fire in the Laramie Mountains of Wyoming burning approximately 39,700 ha. Ponderosa pine (*Pinus ponderosa* P. & C. Lawson) mortality due to the high-severity fire was 95% 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 reduction of seed supplies from living trees, warm temperatures, and limited precipitation. Wildfire intensity and frequency is predicted to increase with climate change and ponderosa pine forests are incredibly susceptible to this dramatic shift. The purpose of this research was to determine the best restoration treatments for ponderosa pine regeneration and seedling survival in a Wyoming ponderosa pine forest post high-severity fire.

Results

Our results indicate that the pine introduction treatment 'planted seedlings' was the most effective restoration treatment in semi-arid, mid-elevation sites, although overall survival rates of seedlings were very low from initial planting numbers. None of logging methods resulted in improved survival of pine seedling or higher regeneration. The estimated mean percent moss cover was higher in the 'no logging' logging method and resulted in a lower mean percent bare ground. Overall, two years after implementation of the restoration treatments did not result in different vegetation communities.

Conclusions

Potential reasons for the lack of restoration effects on vegetation community variables at the Rogers Research Station are likely the large landscape heterogeneity with differing slopes and aspects coupled with the short time frame (2 years) since implementation of the restoration treatments at the site. Further research is needed to determine if restoration treatments will have greater impact on ponderosa pine survival and regeneration in the midterm (6–10) years post implementation. This research is applicable for national, state, and local land managers to implement impactful restoration practices post-wildfire.

Background

Wildfires are increasing in frequency and extent as a result of climate change, fire suppression, and land management. Mid-elevation forests in the Western part of the United States (US), specifically in the Rocky Mountains, 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 kill approximately 80% or greater of the dominant vegetation, including future seed sources — are responsible for the greatest ecological changes in these mid-elevation forests (Kaufmann et al. 2006; Hunter et al. 2007). The understory vegetation community and surface litter may also be completely consumed during a high-severity wildfire if fire intensity is also high, potentially increasing the risk of invasion by non-native plant species (Cowan et al. 2016).

Historically, ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forests in the western US experienced episodic fires that were typically frequent and low-intensity and characterized as surface fires (Jolly et al. 2015). Evidence of climate and fire history provided by historical documents and dendrochronology records show that high-severity wildfires occurring in ponderosa pine forests are strongly associated with the summer wildfire seasons co-occurring with drought years (Westerling et al. 2006). Mid-elevation ponderosa pine forests ranging from 1680 to 2590 m in elevation are most susceptible to an increased wildfire frequency due to typically low precipitation, low moisture indexes, and high temperatures (Westerling et al. 2011; Rother and Veblen 2016).

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 meters from a seed source is the threshold for abundant ponderosa pine regeneration (Bonnet, Schoettle, and Shepperd 2005; Haire and McGarigal 2010; Ouzts et al. 2015; Chambers et al. 2016; Rother and Veblen 2016). Other important factors of ponderosa pine germination and regeneration following a high-severity wildfire include temperature, wind speeds, solar radiation, and soil moisture. 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).

Our paper aims to determine (1) the most effective restoration treatment method for ponderosa pine survival and regeneration at a mid-elevation site in a semi-arid climate and (2) how restoration treatment methods affect vegetation composition, including invasive species. Results from this experiment will aid land managers in the Rocky Mountains in determining the best ponderosa pine regeneration practices to implement after a high-severity wildfire.

Methods

Site Description

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

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*), choke cherry (*Prunus virginiana)*, service berry (*Amelanchier alnifolia*), and Wood's rose (*Rosa woodsii)*.

Forbs included cinquefoil (*Potentilla* spp.), fringed sagewort (*Artemisia frigida)*, geraniums (*Geranium* spp.), milkvetch (*Astragalus* spp.), and yarrow (*Achillea millefolium)*. The dominant grasses and sedges that occur were bluebunch wheatgrass (*Pseudoroegneria spicata*), wild Idaho fescue (*Festuca idahoenis)*, prairie junegrass (*Koeleria macrantha*), and Geyer's sedge (*Carex geyeri*) (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 200–500 ºC 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).

According to (Seymour, Driese, and Waggener 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.

Study design

A 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 x 50 m (0.25 ha) in size.

Each plot received different combinations of a pine introduction method (natural regeneration, broadcast seeding, and planted seedlings), a logging method (no logging, bole only removal, whole tree removal), and an erosion control seeding (no erosion seeding and seeding with a native grass 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 x 27m (0.07 ha) in the center of each plot. From here on logging methods 'bole only removal' and 'whole tree removal' will be referred to as 'bole only' and 'whole tree'.

In total 2,400 one year old, nursery grown ponderosa pine seedlings were planted in all 'planted seedling' pine introduction treatments with 100 seedlings planted per plot 3 m apart in a grid system within the inner subplot. Nursery stock came from Colorado State Forestry Nursery in Fort Collins, Colorado. 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. Seeds were dispersed using a hand-held broadcast seeder at 158 grams per subplot.

The erosion treatment was implemented by broadcast seeding native grass species; included in the erosion grass seed mix were 'Bromar' mountain bromegrass (*Bromus marginatus*), 'Lodorm' green needlegrass (*Nassella viridula*), 'Pryor' slender wheatgrass (*Elymus trachycaulus*), and 'Winchester' Idaho fescue (*Festuca idahoensis*) with 92% germination viability. Treatments were randomly assigned to plots based on the feasibility of a treatment establishment as determined by slope and topography of a plot (Herget et al. 2018).

Seedling surveys

Ponderosa pine seedling surveys were done for all pine introduction treatments in the summer of 2017, while 'planted seedlings' plots were also surveyed in 2015, one to two months after seedlings were planted and in the fall of 2016. Surveys were conducted by walking each subplot in 3 x 3 m grids and 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 the summer of 2017 (June and July) 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 using the Daubenmire method for vegetation cover. Percent bare ground, ground cover (rock, lichen, litter, and woody litter), and both native and non-native plant species cover were recorded in each quadrat (Coulloudon et al. 1996).

Statistical analyses

We were interested in the mean of ponderosa pine seedlings, vegetation functional groups, and ground cover among the three pine introduction methods and the three logging methods, and the combination of these factors at the Rogers Research Site. Comparisons of interest were carefully planned and defined before any data was collected, therefore no multiple comparison adjustments were used. All statistical analyses were done in R version 4.0.3 (R Core Team 2020).

We fitted a Bayesian linear mixed-effect model with a negative binomial distribution using ponderosa pine seedling counts as the response variable, pine introduction method and logging method and their interaction as the fixed effects, and block as the random effect using the blme package (Chung et al. 2015) and lme4 package (Bates et al. 2014).

We fitted 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 and logging methods at RRS using the glmmTMB package (Brooks et al., 2017). The mean functional group cover and ground cover were the response variable, pine introduction and logging methods were the fixed effects, and block was the random effect.

The model with the lowest AIC score was chosen to determine what 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 method, logging method, and erosion control seeding 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 was derived using the emmeans package (Lenth 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 method, logging method, and erosion control seeding.

A permutational multivariate analysis of variance (PERMANOVA) with a Bray-Curtis dissimilarity index was used to determine the effect of logging and pine introduction methods and erosion seeding on the vegetation functional groups using the adonis function in the vegan package. (Oksanen et al. 2020). Permutations were constrained using block. Pairwise comparisons with a Bonferroni correction was done among logging methods and pine introduction methods using the pairwise.perm.manova function in the RVAideMemoire package (Hervé 2021).

Results

Ponderosa pine introduction

While in late summer 2015 1,992 out of the 2,400 planted seedling were still alive, this had reduced to 199 in the fall 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) method and 9 seedlings in the 'natural regeneration' (average of 0.4 ± 1.4 per plot) method. The pine introduction method (X^2 (2, N = 72) = 58.4, p = < 0.001) and the logging method (X^2 (2, N = 72) = 10.8, p = 0.004) had a separate significant overall treatment effect on the estimated mean ponderosa pine stems ha^{-1}. However, the interaction between the two methods did not significantly differ from the null hypothesis of no overall treatment effect (X^2 (4, N = 72) = 2.7, p = 0.7) (Table 1).

The 'planted seedlings' ponderosa pine introduction method within the 'bole only' and 'whole tree' logging methods had significantly higher estimated means of ponderosa pine seedling stems ha^{-1} compared to the 'natural regeneration' and 'broadcast seeding' pine introduction methods within the same logging methods (Fig. 2). Ponderosa pine estimated mean stems ha^{-1} in the 'planted seedlings' pine introduction method in combination with the 'whole tree' logging method (2,596 stems ha^{-1} (95% CI 939 to 7,176 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 method plots (772 stems ha^{-1} (95% CI 264 to 2,252 stems ha^{-1}), and almost two times greater than the 'planted seedlings' and 'bole only' plots (1,307 stems ha^{-1} (95% CI 462 to 3,699 stems ha^{-1}) (Table 1). The estimated mean ponderosa pine stems ha^{-1} in the 'planted seedlings' and 'no logging' plots were 3-fold and 12-fold 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 or only marginally significantly different, respectively (p = 0.5, p = 0.09).

Vegetation functional groups and ground cover

Overall, none of the logging or pine introduction methods had a significant effect on the percent cover of vegetation functional groups, except for mosses (X^2 (2, N = 72) = 23.1, p = < 0.01, Table 2). In addition, PERMANOVA indicated that the overall composition of vegetation functional groups was not affected by any of the logging methods, pine introduction methods, or erosion treatment. 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.

Overall, logging methods had a treatment effect on the estimated mean percent moss cover (X^2 (2, N = 72) = 23.1, p = < 0.01), and a marginal overall treatment effect on the estimated mean percent bare ground (X^2 (2, N = 72) = 5.73, p = 0.06). The pine introduction methods had no overall treatment effect on either the estimated mean percent moss cover (X^2 (2, N = 72) = 5.4, p = 0.07) or bare ground (X^2 (2, N = 72) = 0.04, p = 1.0) (Table 2). The estimated mean percent moss cover in the 'no logging' logging method 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 methods, respectively (Fig. 3A). Conversely, the estimated mean percent bare ground in the 'no logging' logging method was estimated to be 9.7 times lower (95% CI 7.6 to 12.3 lower) and 7.7 times lower (CI 95% 6 to 9.7 lower) than the 'bole only' and 'whole tree' logging methods, respectively (Fig. 3B). In a seperate model, erosion control seeding in addition to the pine introduction method and the logging method 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 method (X^2 (2, N = 72) = 17.4, p = < 0.001) in this model.

Although the estimated mean percent woody cover was not significantly different among the three logging methods, there was an overall treatment effect of logging method (X^2 (2, N = 72) = 6.73, p = 0.03) (Table 2).

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

Only two of the four seeded grass species from the erosion mix, field brome (*Bromus marginatus*) and green needlegrass (*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 = < 0.01).

Discussion

Restoration 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 methods, the total survival for ‘planted seedlings’ treatment two 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 University 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.

One approach to enhance seedling survival, would be to optimize the planting pattern. Rather than planting ponderosa pine seedlings in grid patterns (a common timber industry practice for lumber production), seedlings should be planted in microsites — areas on the landscape that protect seedlings from wind and solar radiation and provide adequate soil moisture: utilize boulders, remaining boles, logs, woody debris, and depressions on the landscape.

Another approach to enhance seedling survival during early stages of establishment is inoculation with mycorrhizal fungi (Maltz and Treseder 2015). Seedlings inoculated with ectomycorrhizal fungi (ECM) enhances nutrient uptake from the soil via the ECM hyphae to the host species’ roots after being planted to reduce environmental stressors on seedlings (Smith and Read 2008, Simard et al. 2012). In our study, the planted seedlings were inoculated with commercially available ectomycorrhizal fungi during growth at the Colorado State Forestry Nursery. Although, mycorrhizal fungi in general can enhance seedling survival, research has shown a significant increase in percent survival (20–35% increase) of Aleppo pine (*Pinus halepensis* Mill.) seedlings inoculated with specifically selected ECM species adapted to environmental site conditions compared to seedlings inoculated with other ECM species (Rincón, De Felipe, and Fernández-Pascual 2007). Thus, to further increase survival of ponderosa pine seedlings in semi-arid conditions, nurseries should consider inoculating seedlings with ‘local’ ECM species — ECM inoculum derived from soil from the actual site or the same environment seedlings will be planted in (Maltz and Treseder 2015). In fact, in a greenhouse experiment, ponderosa pine seedlings grown in soil from nearby low-severity burn plots with living mature ponderosa pines at RRS had higher above and belowground biomass and more mycorrhizal colonization compared to seedlings grown in soils collected from the high-severity restoration plots with no living ponderosa pines (van Diepen, unpublished data). Further research is needed to determine if planting ponderosa pine seedlings inoculated with ‘local’ ECM will improve survival rates, compared to seedlings inoculated with the commercial ECM at the RRS.

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 methods. Low germination rates of ponderosa pine seeds occur from failure of roots to establish, herbivory, desiccation, and cold temperatures in winters (Stein and Kimberling 2003). Reitveld and Hiedmann (1976) compared spot seeding (planting seeds directly into the soil) versus broadcast seeding methods of ponderosa pine post-wildfire and found that spot seeding resulted in higher germination rates (3,800 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, Schoettle, and Shepperd 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 is 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) .

Although there was an overall treatment effect of the logging methods for stem density, logging methods did not effectively increase ponderosa pine seedling survival or regeneration in any pine introduction methods. Similar results were found by Ritchie et al. (2009) with no significant effect on the growth of planted seedlings by salvage logging treatment. Other 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).

Restoration treatments effect on vegetation and ground cover

Logging post high-severity wildfire in a semi-arid environment is an additional disturbance to a site which was also observed at our study site with lower percent moss cover and higher percent bare ground in the logging compared to the ‘no logging’ method; removal of stems and logs with logging equipment remove 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 methods for these individual vegetation functional groups.

Similarly, Keyser et al. (2009) 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 method 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*). But it is unknown if those two species were the seeded 'Bromar' mountain bromegrass and 'Lodorm' green needlegrass variety or if they were grasses that had regenerated post wildfire. Erosion seeding results were inconclusive despite statistical significance; erosion seeding occurred three years post-fire and native perennial grass species present at RRS had already established robust populations requiring seeded perennial grasses to compete for space and resources. Seeding as an erosion treatment post-wildfire is a common practice employed to help stabilize soil and prevent invasive species colonization, but this practice seems unnecessary. In a meta-analysis of 94 papers only one out of ten erosion studies found that erosion was reduced post-precipitation events two years after seeding post-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, Sieg, and FuÍ 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 semiarid, mid-elevation, high-severity burn site within three years post-wildfire. Ponderosa pine seedling survival rates were low in the planted seedling method but even in the logging treatment with the lowest seedlings, stems ha^{-1} planted seedling density was still much greater than recorded current and historical densities of ponderosa pine in the Front Range based on dendrochronology records. Natural regeneration stem ha^{-1} are more within the range with historical ponderosa pine densities in all logging methods. However, with increasing temperatures, limited precipitation, and increased wildfire frequency in semiarid environments of the Rocky Mountains it is advised that to aid in the regeneration of a resilient ponderosa pine forest, land mangers should plant seedlings using an ecological lens. Modifications need to be made to the planting scheme: use of site microclimates provided by coarse woody debris and the natural topography of the site, and ponderosa pine seedlings should only be planted in the spring or fall. Additionally, further research is needed to determine if ponderosa pine seedlings inoculated with 'local' ectomycorrhiza, collected from soils less affected by a high-severity wildfire, will increase planted seedling survival rates.

Salvage logging and erosion seeding did not increase ponderosa pine survival or regeneration in semiarid and mid-elevation sites in the Wyoming Rocky Mountain Front Range. Both are costly and money saved from not implementing these methods could be spent on planting more seedlings if survival rates are low. Salvage logging is also considered an initial disturbance after a natural disturbance and negatively impacts ground cover such as mosses, regardless of slash retention, and increases bare ground.

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 semiarid and mid-elevation regions.

List Of Abbreviations

B
broadcast seeding
BO
bole only removal
CSFS
Colorado State University Forest Service
ECM
ectomycorrhizal fungi
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

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

The authors of this manuscript consent to publication.

Availability of data and material

The datasets used and analyzed are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

Funding for this project was provided by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, McIntire-Stennis Capacity Grant Accession No. 1011356.

Authors' contributions

SW collected and analyzed the data and wrote the paper. LVD was the project PI, acquired the funding, helped with data collection, and edited the manuscript. The authors read and approved the final manuscript.

Acknowledgments

We would like to thank K. Kline, T. Simpson, L. Mann, G. Custer, E. Van Syoc, and P. Ayayee for their assistance in the field and laboratory. Statistical consulting was provided by A. Muldoon. Prior research and implementation of the restoration plots at the Rogers Research Site was led by S. Williams and M. Herget. The Rogers Research Site was bequeathed to the University of Wyoming in 2002 by William Catesby Rogers.

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Tables

Table 1. Ponderosa pine estimated means and 95% confidence interval (CI) of stems ha^{-1} and stems $27m^{-2}$ for Logging methods and Pine introduction methods for the Rogers Research Site, Northern Laramie Mountains, Wyoming as measured in summer 2017.

Logging method[1]	Pine introduction method[1]	Estimated stems ha^{-1}	95% CI	Estimated stems 27m $^{-2}$	95% CI
No logging	Natural regeneration	41	8, 215	0.11	0.02, 0.58
	Broadcast seeding	12	1, 168	0.03	0, 0.45
	Planted seedlings	772	264, 2 252	2.08	0.71, 6.08
Bole only	Natural regeneration	16	1, 188	0.04	0, 0.51
	Broadcast seeding	27	3, 272	0.07	0.01, 0.74
	Planted seedlings	1 307	462, 3 699	3.53	1.25, 9.99
Whole tree	Natural regeneration	215	62, 753	0.58	0.17, 2.03
	Broadcast seeding	67	12, 367	0.18	0.03, 0.99
	Planted seedlings	2 596	939, 7 176	7.01	2.54, 19.37
[1]The overall method effect was significantly different than the null hypothesis (Pr>ChiSq)					

Table 2. Estimated mean percent vegetation functional groups and ground cover, associated 95% confidence interval (CI) and Wald chi-square p-value for logging methods: 'no logging', 'bole only', and 'whole tree' and pine introduction methods: '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			Natural regeneration		Broadcast seeding		Planted seedlings		
	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Pr > ChiSq[1]	Estimate	95% CI	Estimate	95% CI	Estimate	95% CI	Pr > ChiSq
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
[1]Wald chi-square test														

Figures

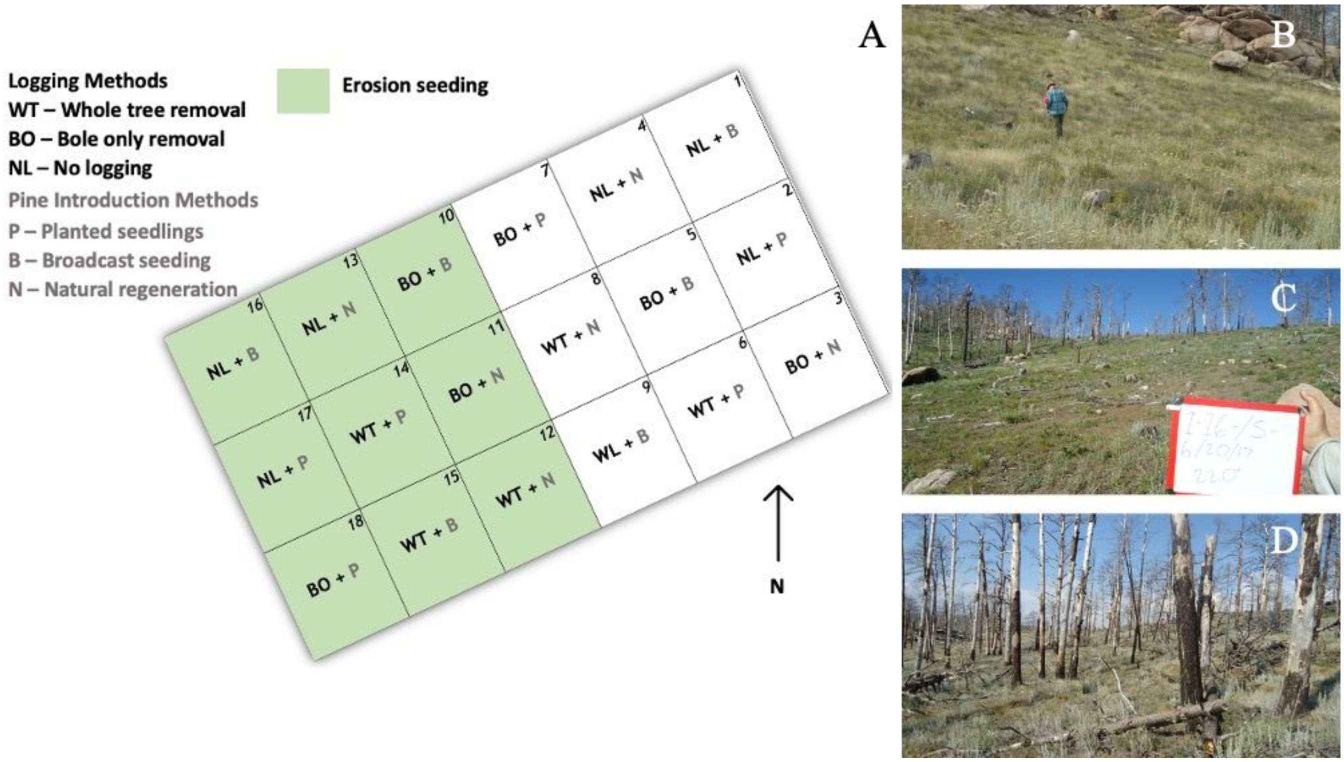

Figure 1

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

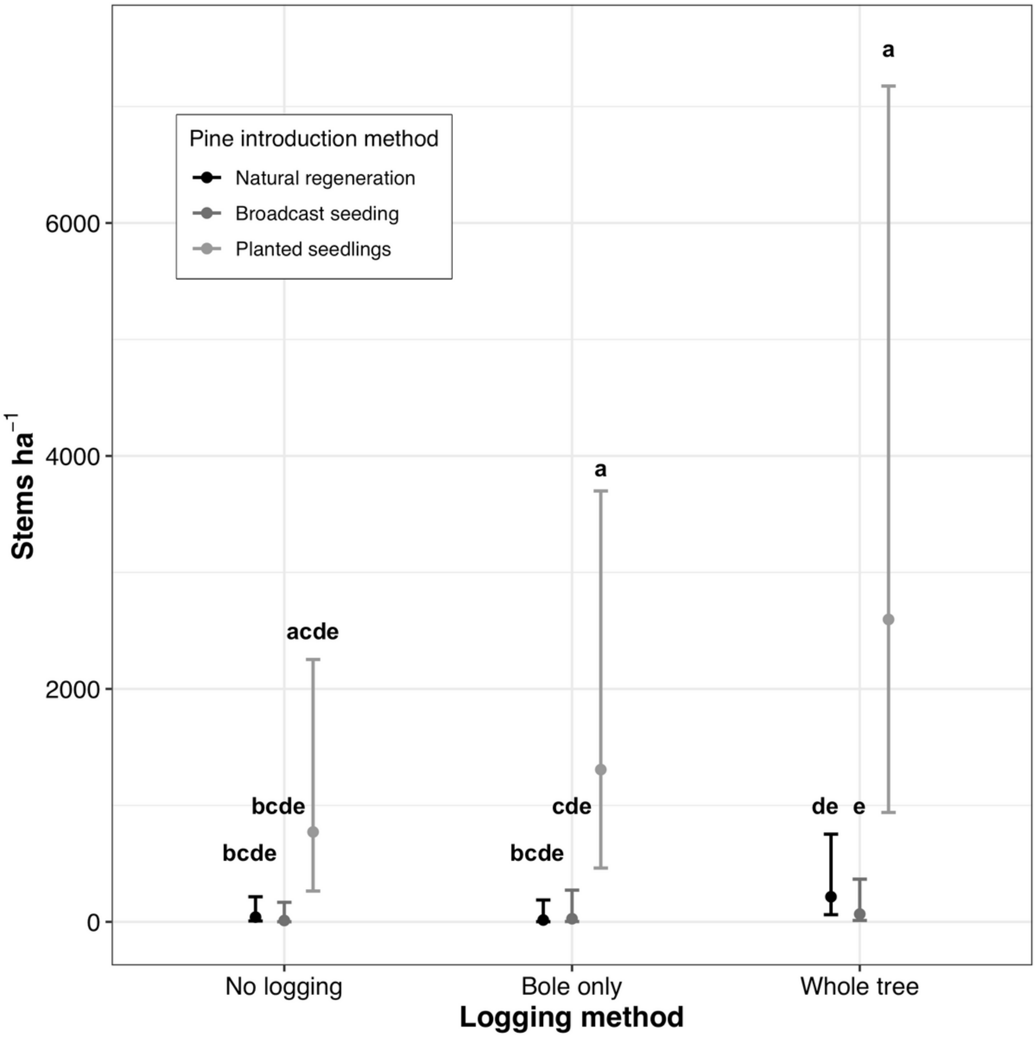

Figure 2

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 methods combined with the three different logging methods.

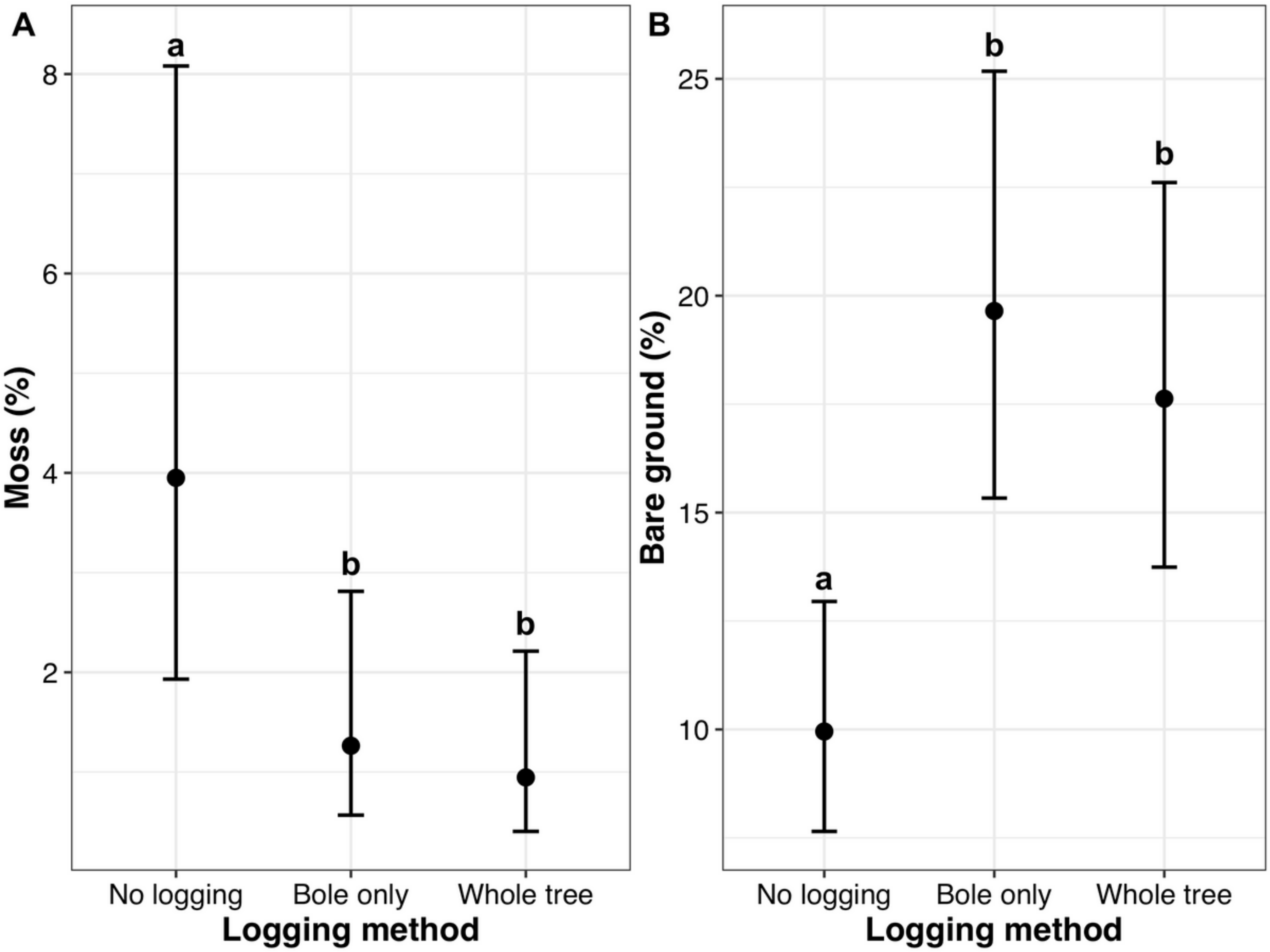

Figure 3

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