FINAL REPORT

Title: Elucidating and Disseminating the Role of Fire Mosses in Post-Fire Ecosystem Recovery

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List of Abbreviations/Acronyms

BAER: Burned Area Emergency Response
NH_4^+: Ammonia
NO_3^-: Nitrate
PRS: Plant Root Simulator
SNOTEL: Snow Telemetry

Keywords

Post-fire, Burned Area Emergency Response, Fire Moss, Salvage logging, Nitrogen

Acknowledgements

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Abstract

The extent of severely burned landscapes are increasing in the Western US due to climate change and altered forest states. Directly after a wildfire, managers implement techniques to stabilize soils or harvest merchantable timber. Collaborating with land managers from the Colville National Forest in Northeastern Washington we built upon a postfire erosion study they had begun. On the 2015 Stickpin Fire, we examined the effects of no treatment, straw mulching, wood shred mulching, and postfire logging on fire moss cover. Fire mosses are non-vascular bryophytes that can rapidly stabilize soils after wildfires. We also examined the cascading effects of moss colonization on postfire nitrogen availability using plant root simulator probes during a winter, October through April, and a spring, April through June, sampling phase.

Consistent with our hypothesis, wood shred mulch, straw mulch, and litter cover inhibited moss cover ($F=13.8$, $p=0.001$) across all treatments by reducing the amount of bare soil cover that moss could colonize. Moss colonization was lowest under the straw mulching treatment, but this was likely linked to the fact that straw mulching occurred on a more south facing hillslope that received more direct sunlight. Additionally, we hypothesized that postfire logging would disturb soils reducing moss cover there. We found that moss cover was reduced on some logging skid trails but increased on others when compared to undisturbed hillslopes ($t=-1.58$, $p=0.14$). This unexpected result points to the potential for mosses to be used in restoration of skid trails after postfire logging as they often have high erosion rates.

Finally, we explored the impacts of moss colonization on nitrogen availability in the soil surface. Moss cover did not affect ammonia (NH_4^+) availability ($F=0.14$, $p=0.71$) but was negatively related to nitrate (NO_3^-) availability ($F=14.3$, $p<0.001$), especially during the winter vascular plant dormancy phase vs the spring active phase ($F=32.7$, $p<0.001$). We believe this due to uptake of NO_3^- by mosses throughout the winter. Moss uptake of NO_3^- could reduce vascular plant growth in the short term if nitrogen is limiting, but over a longer term it could also reduce nitrogen loss via leaching and runoff to surface water during spring snowmelt. This research provides a series of results that point to valuable next steps in fire moss research.

1. Project Objectives

1. Measure moss cover in response to different mulching materials and application rates. We hypothesize that moss colonization will be higher in units with lower mulch cover, irrespective of treatment type.

Completed. Moss cover was measured in Oct 2018 and June 2019 and found to be inversely related to mulch/litter cover. Moss cover was distinctly lower on straw mulched treatments than wood shred and untreated regions. This could be due to hillslope insolation and vascular plant community differences in that treatment.

2. Measure moss cover in response to a salvage logging treatment. We hypothesize that the disturbance of logging will heavily impact moss cover with cascading ecosystem effects.

Completed. We found moss cover ranged widely on postfire logging skid trails from 0 to 52% but was not significantly different from untreated plots.

3. Determine how moss cover changes nitrogen availability in different management settings.

Completed. We found that moss cover reduced NO_3^- availability in an October through April sampling phase with a similar but less strong effect from April through June. We saw no effect of moss cover on NH_4^+ at either time interval.

4. Disseminate information on fire moss colonization, function, and restoration to BAER practitioners and the research community. Increase collaboration between the research and management communities.

Completed. We presented results from this research at three conferences, one BAER coordinators meeting, one webinar, and one fact sheet available via the Southwest Fire Science Consortium. Additionally, Henry Grover coauthored a BAER effectiveness monitoring report and collaborated extensively with land managers in US Forest Service Region 1.

2. Background

The extent of severely burned landscapes is rapidly increasing in the Western US due to climate change and altered forest states (Covington & Moore 1994; Abatzoglou & Williams 2016). Too often, an immediate outcome of severe burns is a pulse of enhanced flooding, soil erosion and debris flow which may threaten human lives and property while restraining forest recovery (Moody & Martin 2001). Managers implement a variety of techniques to either stabilize soils or harvest merchantable timber within burned areas (Beschta et al. 2004; Bautista et al. 2009). To better inform decision making, researchers have studied how these techniques affect communities from wildlife to the vascular plants. One potentially highly functional, but overlooked, community are non-vascular bryophytes that colonize burned landscapes rapidly after wildfires, known as fire mosses. Fire mosses consist of three early successional mosses, *Funaria hygrometrica*, *Bryum argenteum*, and *Ceratodon purpureus* that colonize severely burned soils in temperate forests globally (Hoffman 1966; Southorn 1977; Brasell & Mattay 1984).

Mosses and other biological soil crust components have long been recognized as ecosystem engineers in rangelands for their modification of habitats by altering hydrology, stabilizing soils, and increasing fertility (Bowker et al. 2008; Maestre et al. 2011). However, the ecosystem engineering potential of fire mosses has not been adequately explored in burned forests. Furthermore, we do not know how our post-fire management techniques affect fire mosses. My dissertation focused on better understanding fire mosses as a potential tool for postfire restoration. Mosses increase soil stability and infiltration by over 100% when compared to bare soil in the southwestern US (Grover et al. 2020) and attain almost 50% cover on burned landscapes in the northwestern US within two years of a fire. In this study explore how two Burned Area Emergency Response (BAER) mulching techniques and one postfire logging prescription affect fire moss cover and cascading impacts on soil nitrogen three years after a wildfire. We partnered with the Colville National Forest to examine the 2015 Stickpin Fire in Northeastern Washington. Wood shred and wheat straw mulch was applied to 30-35% slopes where soils had burned at high severity to mitigate erosion risks. A level II BAER effectiveness monitoring study was undertaken to compare erosion reduction associated with untreated, wood shred, and wheat straw hillslopes. Nearby, a postfire salvage logging experiment was implemented to better understand logging's effects on long term fuel loading and tree regeneration. The proximity of these treatments allowed for their direct comparison and the ability to share control units between treatments.

3. Methods

The study was conducted near Deer Creek Summit along the Boulder Creek Rd in 31 miles north west of Kettle Falls Washington (Figure 1A). Initially, 30 silt fence plots were installed in June 2016 after helicopter mulching was completed in late May 2016. These plots were 10 meters tall by 5 meters wide running up the hillslope to monitor mulching's effectiveness at reducing sediment after the wildfire. Plot selection focused on high soil burn severity, west/southwest aspects, and slopes between 20-50 percent.

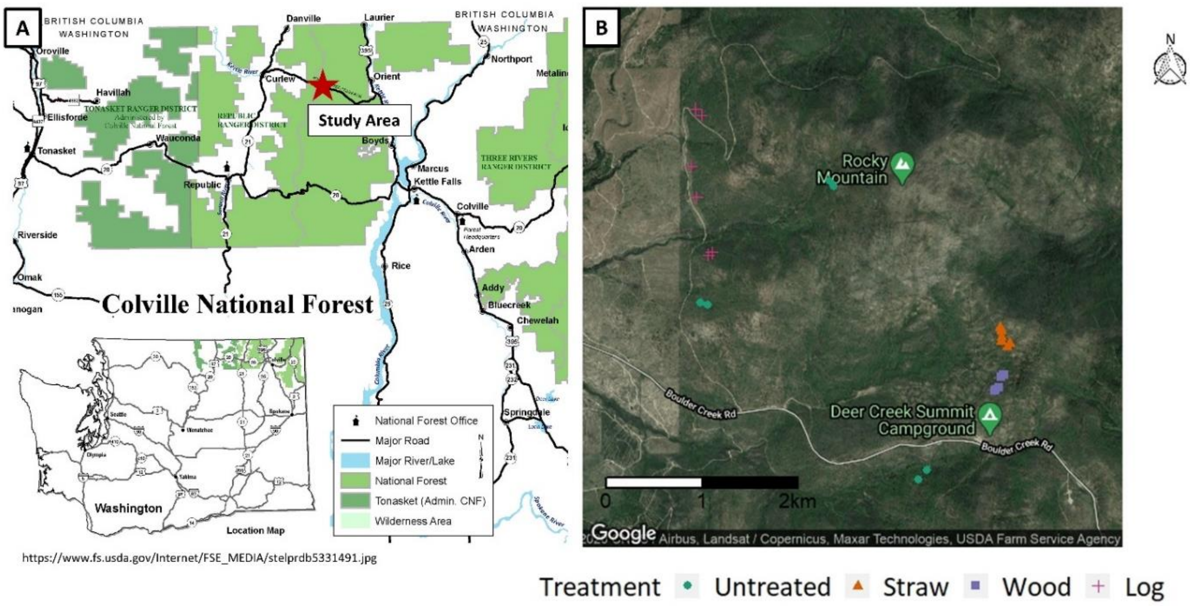

Figure 1: Location of Colville National Forest within Washington State, the study area indicated by a red star (A), and the plot locations withing the study area (B).

For this study, we used a subset of the silt fence plots including six wood shred, six wheat straw, and two untreated plots. The remaining four untreated plots and six logged plots were selected from the surrounding location to match the slope and insolation -the amount of energy from the sun reaching a particular hillslope- of the original plots and to reduce pseudo replication (Figure 1B). To derive insolation, we calculated direct radiation modified by terrain and total diffuse radiation at each hour of the day, but excluded the minimal effects of skyview and changes in relative humidity and temperature throughout the day (Corripio 2003). The postfire salvaged logging treatment prescription was a basal area reduction to 15% of pre-logged density and skid trials rain directly up hillslopes (Johnson et al. 2020). Plots were confined to salvage logging skid trails as these are often the most impacted areas of a salvage logging operation (Wagenbrenner et al. 2015). Four treatment levels by six replicates per treatment created a total of twenty-four experimental units within the study; however to address objectives 1 and 2 we selected only a subset of treatments. The original study design was implemented to maximize management objectives rather that research robustness. Therefore, a limitation of the design was the spatial clustering of plots of the same treatment, leading to some degree of pseudo-replication and correlation of treatments with unmanipulated environmental factors. Nevertheless, the study did offer opportunity to better understand likely effects of treatments on mosses, and mosses on available nutrient, given a cautious interpretation. (Figure 1B). Within each silt fence plot, four ground cover subplots had been established at the top (upper extent), bottom (just above the installed silt fence) and at the center of the left and right sides using a 1m² point-intercept quadrat (Figure 2).

Figure 2: Photos of each treatment looking upslope from the bottom of a plot, October 2018. Quadrat in foreground is 1x1meters. Moss can be seen in foreground of Untreated photo.

Cover was recorded at 10 cm intervals with 100 points at the bottom and top of each plot, and 50 on each side, for 300 total points. A similar subplot layout was used for establishing new plots; however, logging subplots were restricted to the width of skid trails to maintain equal disturbance within those plots. Cover types of bare soil, fine litter, live vegetation, woody debris, gravel, rock, standing dead, moss, and treatment were recorded. Data was collected in October of 2018 and late June of 2019.

Vegetation recovery and straw mulch decomposition was high due above average precipitation (Figure 3). Because of this, we found it especially hard to differentiate between straw mulch and grass litter three years after mulch installation. Additionally, straw mulch was not completely sterile and high coverage of barley had germinated which we wanted to capture as a treatment induced increase in ground cover. Treatment, fine litter, and woody litter values were combined for analysis to allow for the effects of mulching and barley, essentially a large increase in litter, to be represented as a single number.

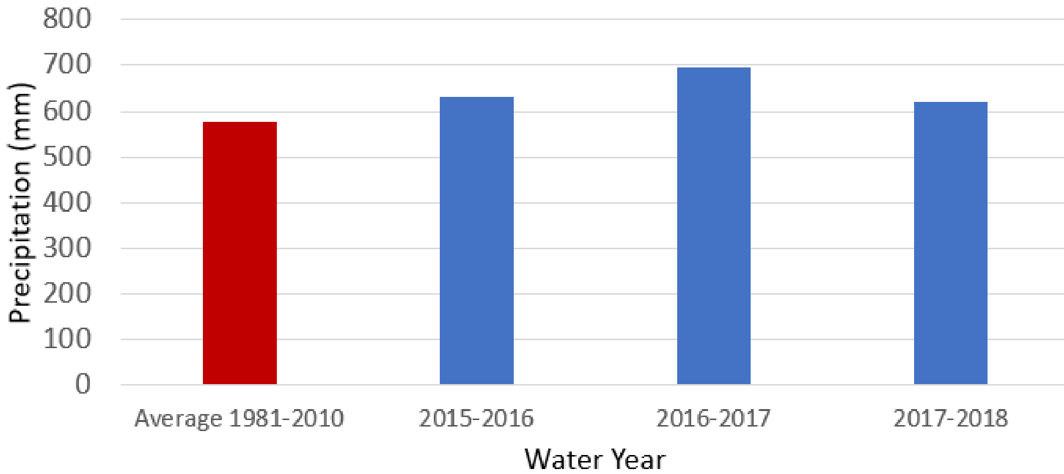

Figure 3: 30-year average precipitation and postfire precipitation for the three water years following the fire until the end of the study. Data was collected from the Sentinel Butte SNOTEL site located on Deer Creek Pass. Water years in northeastern Washington begin on October 1st and end September 30th.

To measure soil nitrogen, we used Plant Root Simulator ion exchange probes. These probes uptake ions over time to allow for an extended quantification of nutrient availability to plants. Probes were installed during two seasons winter (October-April) and spring (April-June). In the winter nutrient mineralizing microbes remain active while vascular plants go dormant and nutrient availability is often at its highest by early spring. By early summer, vascular plants have become active and harvested available nutrients allowing for a better understanding of nutrient dynamics when availability is low. One cation and anion probe were installed at each subplot for a total of eight probes per plot. Probes were buried with resin membranes 0-2cm deep to measure the near surface effects of moss colonization, mulching, and logging disturbance. Upon extraction, probes from each plot were washed thoroughly with deionized water, placed into plastic bags, and shipped in a cooler for analysis. At Western Ag Innovations, the probes were extracted with 17.5 ml of 0.5 N HCl for 1 hour in a zip-lock bag, and the extractant was analyzed for NH_{4+} and NO_{3-}colorimetrically using a Technicon AutoAnalyzer II (Seal Analytical, Mequon, WI).

All statistical analysis was performed in R (R Core Team 2019) by building linear mixed effects models using the lmerTest package (Kuznetsova et al. 2017). All models met assumptions of linearity, equal variance, and normality either before or after data transformations. Because plots were sampled in both fall 2018 and spring 2019, we added a random effect of plot to every model to account for temporal autocorrelation. To model mulching effects on moss cover we performed analysis of covariance. This model included a categorical predictor of treatment, and a continuous predictor of mulch/litter cover. We tested for an interaction between the predictors, but it was too weak to justify inclusion in the model. To analyze the effects of logging on moss cover we used a two-sample t-test and moss cover was square root transformed. The effects of moss cover on Ammonia (NH_4^+) and Nitrate (NO_3^-) was determined using analysis of covariance with a continuous predictor of moss cover, a categorical predictor of season, and their interaction.

4. Results and Discussion:

Objective 1: Measure moss cover in response to different mulching materials and application rates.

As hypothesized, moss cover was inversely related to mulch/litter cover throughout the study (Figure 4). This relationship was similar across straw mulched, wood shred mulched, and untreated plots with no interaction between mulch/litter cover and treatment ($F=1.33$, $p=.29$). Maximum moss cover was 46.5% on an untreated plot at 35% mulch/litter cover and minimum was 3.4% on a straw mulched plot that had 76.3% mulch/litter cover.

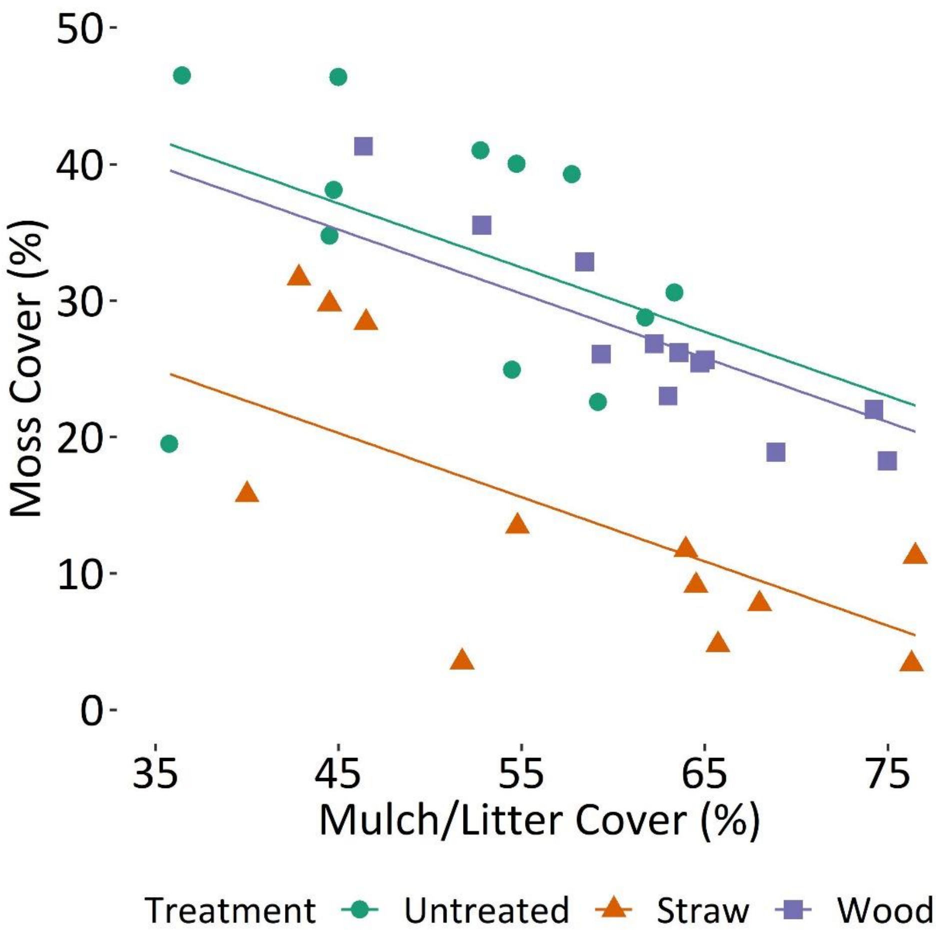

Figure 4: Moss cover as a function of litter and mulch cover ($F=13.8$, $p=0.001$) by treatment type ($F=16.4$, $p<0.001$). Lines are model predictions ($R^2 = 0.64$). Mulch/litter cover includes fine litter, woody litter, and treatment.

Average moss cover was highest in untreated plots and lowest in straw mulched plots (Table 1). Average mulch/litter cover was highest in wood mulched plots due to the persistence of wood mulch on hillslopes through time and lowest in untreated plots but these treatments only differed by 12 percentage points (Table 1). Although mulching increases the relative abundance of organic versus mineral materials, these results are inconsistent with a greenhouse experiment showing that fire mosses grew better on an organic substrate than a mineral soil substrate (Grover et al. 2019). The organic substrate in the greenhouse experiment was more decomposed, fully saturated with water, and in a climate-controlled environment, however. Perhaps most importantly, it was not applied as a mulch. The decreased moss cover on straw mulched plots may be an outcome of that particular treatment, but could be at least partially explained by higher insolation values on the hillslope where straw mulch was applied (Table 1).

Table 1: Mean values for mulch/litter cover, moss cover, and insolation across all plots measured for objective 1.

Treatment	Mulch/Litter Cover (%)	Moss Cover (%)	Insolation (Mj m^{-2})
Untreated	50.9	34.4	16.6
Straw	57.9	14.2	19.5
Wood	62.8	26.8	16.8

Insolation was found to have a strong inhibitory effect on moss cover in a landscape scale survey of moss colonization in the Southwestern US (Grover et al. 2020). Another potential explanation is that the barley colonizing the straw mulched hillslope inhibited moss growth. Grasses acquire moisture from the topmost layer of soil when it is available thus decreasing the mosses available water (Nippert & Knapp 2007). In contrast, on a north facing slope in the Gila National Forest grass seeding increased post fire moss colonization by 12% compared to untreated plots two years after a wildfire (Koehler & Keisow 2016). At this time, the relationship between fire moss and vascular plant colonization is not well understood and should be studied further before drawing firm conclusions

Objective 2: Measure moss cover in response to a salvage logging treatment.

Contrary to our hypothesis, moss cover was not significantly higher in untreated plots then in logged plots (Figure 5). There was a much higher range in moss cover on logged plots (0- 52.4%) than in untreated plots (19.5-46.5%). We found skid trails with low moss cover had been more disturbed with lower soil surface bulk density, likely due to more passes by skidders on steeper slopes. Recent studies have shown that skid trials are often the largest contributors to postfire erosion but remediation through slash additions can be effective at reducing sediment production (Robichaud, Lewis, et al. 2020; Prats et al. 2020). Moss is another potentially important contributor to skid trail recovery due to their ability recolonize these disturbed areas but exactly what is driving colonization success should researched in more detail to illuminate potential ways to improve that success. Moss cover did reduce the amount of plant available NO_3^- on skid tracks as outlined in the next objective. This could be valuable for reducing nitrogen pollution inputs to waterways where elevated NO_3^- can persist for years after fires, and be more easily transported to streams via skid trials (Bladon et al. 2008; Robichaud, Bone, et al. 2020).

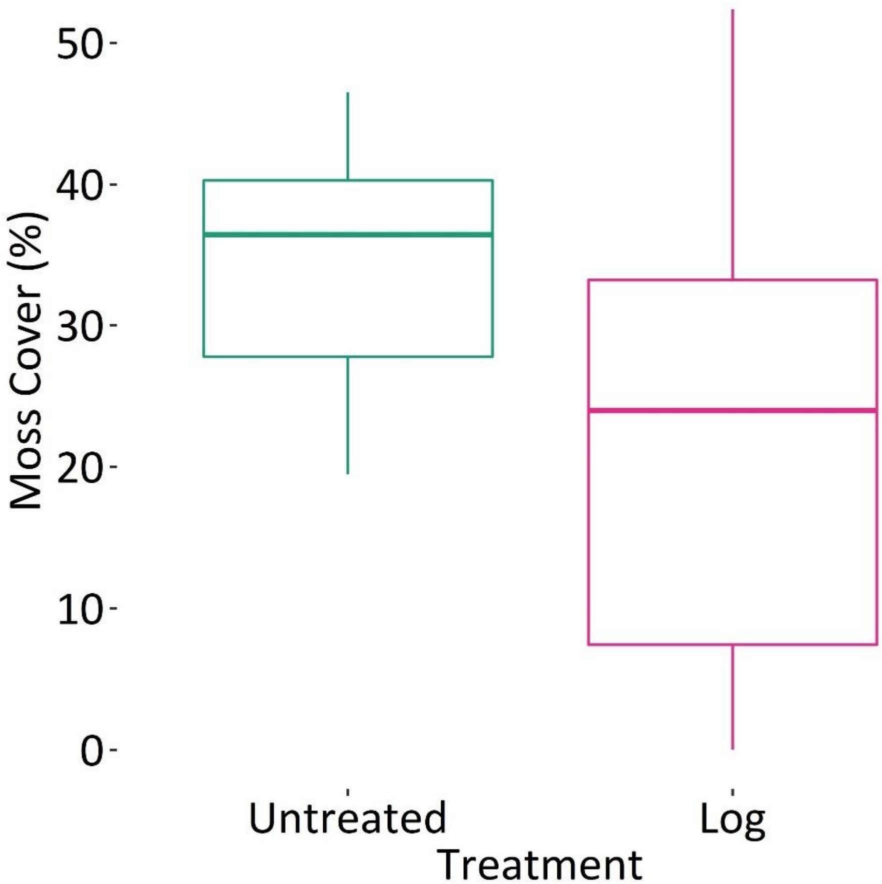

Figure 5: Boxplot of moss cover on untreated and salvaged logged plots (t=-1.58, p=0.14). Bars represent location of upper and lower 25% of data points and boxes middle 50% of data points.

Objective 3: Determine how moss cover changes nitrogen availability in different management settings.

Nitrogen is among the chief limiting nutrients in terrestrial, freshwater and marine ecosystems (Elser et al. 2007). Terrestrial plants strongly favor mineral forms of N over organic ones, and except in wetter environments, prefer NO_3^- to NH_4^+ owing to its greater mobility (Wang & Macko 2011). We found that available nitrogen is apparently affected by fire moss cover, though not in the way we had hypothesized. We expected that more moss cover would be associated with greater available nitrogen in the soil surface, but instead observed that NH_4^+ is not related to moss cover (Figure 6), and NO_3^- is inversely related to moss cover. Furthermore, this relationship was stronger in winter than spring (Figure 7).

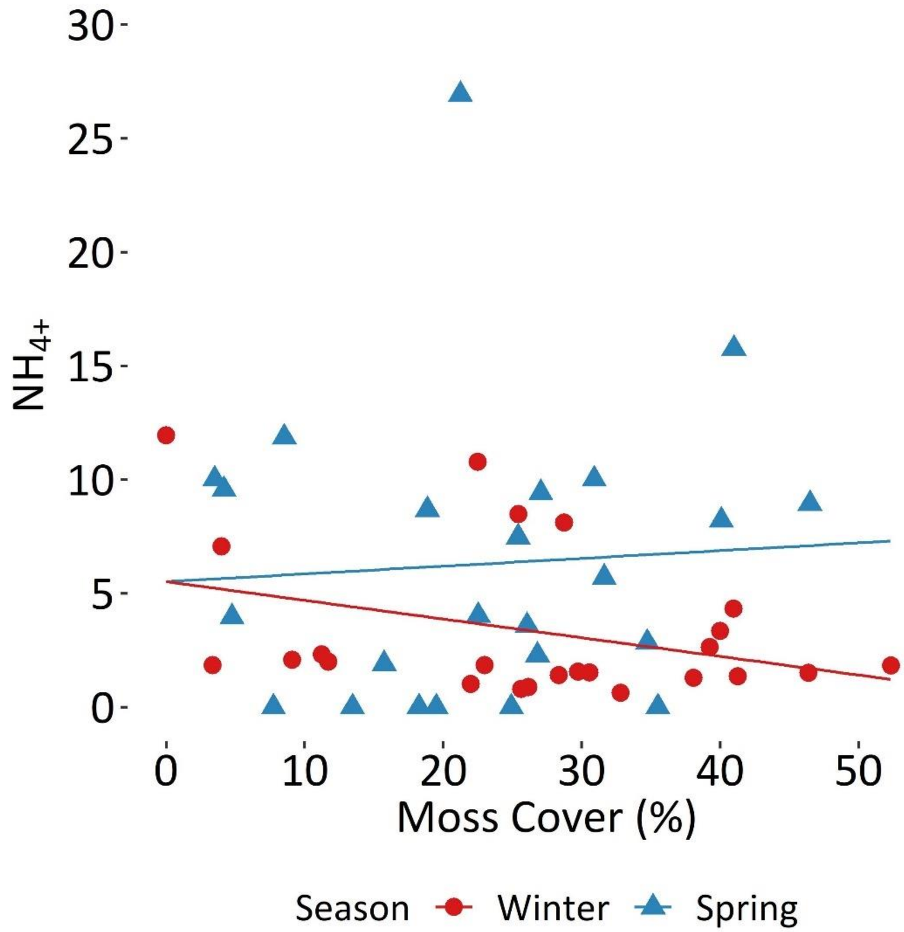

Figure 6: NH_4^+ (mg m^{-2} burial days $^{-1}$) as a function of moss cover ($F=0.14$, $p=0.71$), burial season ($F=0.00$, $p=0.99$), and their interaction ($F=1.6$, $p=0.21$). Data from all treatment levels were combined for this analysis.

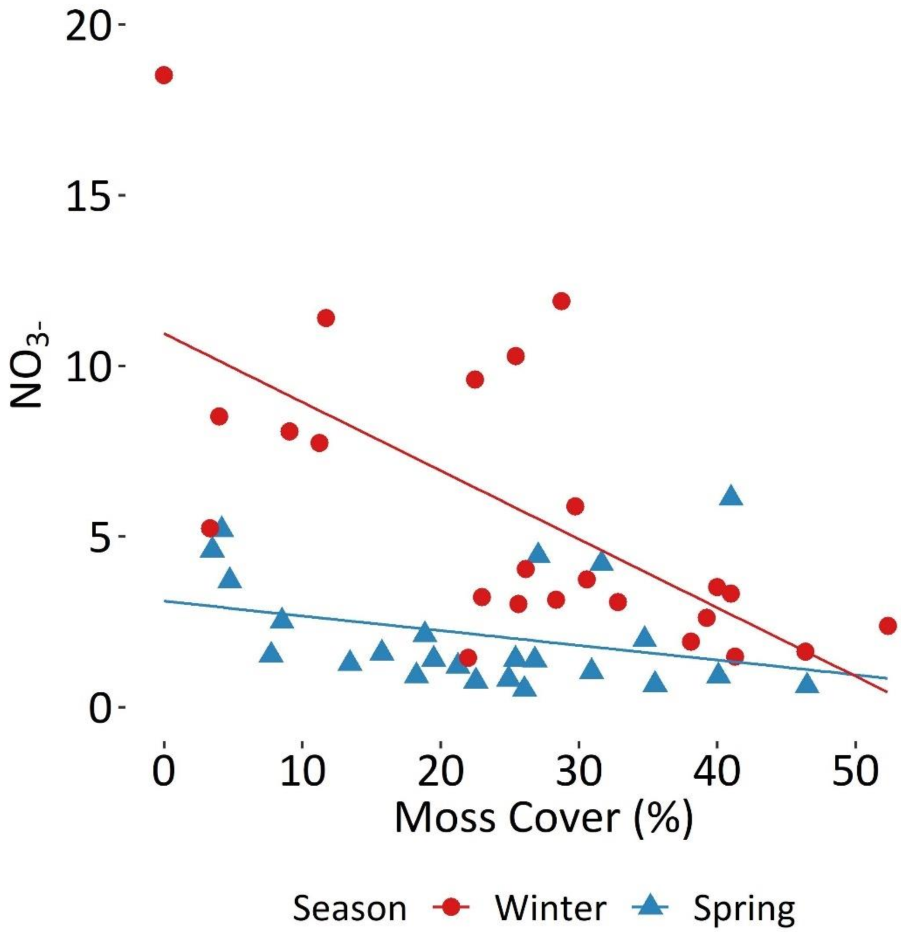

Figure 7: NO_3^- (mg m^{-2} burial days $^{-1}$) as a function of moss cover ($F=14.3$, $p<0.001$), burial season ($F=32.7$, $p<0.001$), and their interaction ($F=9.9$, $p=0.004$). Data from all treatment levels were combined for this analysis.

There are multiple mechanisms that could explain this pattern or contribute toward explaining it. NO_3^- outputs from the soil solution include erosion, uptake by plants, immobilization and denitrification by microbes, leaching, and erosion. The chief NO_{3-} input to the soil solution is nitrification. We must ask if mosses may promote an output or suppress an input.

Might mosses enhance NO_3^- losses through increased erosion? Nitrogen loss due to erosion after fire is variable but can be significant (3 - 110 kg N ha-1) over four post-fire years (Pierson et al. 2019). All available evidence suggests that fire mosses stabilize soil and decrease erosion (Grover et al 2020, Silva et al. 2019). Further, no erosion was ever detected on these plots. Finally, erosion losses would not be expected to discriminate between NO_3^- and NH_4^+, but these two N species exhibit very different responses to mosses. This explanation is highly unlikely.

Might mosses enhance NO_3^- losses through increased leaching? Prior data suggests fire mosses enhance infiltration (Grover et al. 2020), therefore perhaps they facilitate transport of highly mobile NO_{3-} into the soil below our point of measurement. However, if this were the main reason why NO_{3-} and mosses negatively correlate, we would expect stronger patterns in Spring when snowmelt and rain occurs rather than in winter when soils would often be frozen, and precipitation falls mostly as snow. This explanation is unlikely.

Might mosses suppress NO_{3-} gain by suppressing nitrification? Apparent suppression of nitrification by lichen-dominated biocrusts in drylands (Delgado-Baquerizo et al. 2010), and moss-dominated biocrusts in humid karst regions (Hu et al. 2019) has been observed. Allelopathy has been speculated as a possible mechanism (Delgado-Baquerizo et a. 2010), but modification of the soil environment, e.g. soil moisture, is also plausible. If the sole reason why NO_3^- declines in suppressed nitrification by mosses, then we would expect more NH_4^+ where mosses are abundant because NH_{4+} is the substrate of nitrification. We did not detect such a pattern. This explanation is plausible, but incomplete.

Might mosses enhance NO_3^- loss by stimulating immobilization by microbes? Enhanced supply of C to soils can promote the consumption of N by microbes (immobilization). Mosses are plausible C sources for microbes (Slate et al. 2019). However, if our data were explained by immobilization, we would expect a much weaker relationship between mosses and NO_3^- in the winter when both fungal and bacterial metabolism is much slower (Pietikäinen et al. 2005). This explanation is plausible, but incomplete.

Might mosses enhance NO_3^- loss by stimulating denitrification? As with nitrification, it is plausible that mosses could alter the soil environment in such a way as to favor denitrification, e.g., by increasing soil moisture and promoting reducing conditions or though the release of exudates (Slate et al. 2019). As with immobilization, we would not expect a stronger effect in winter for two reasons: denitrification is cold-limited (Öquist et al. 2004), and moss exudates which might stimulate microbial activity are more prevalent after dehydration-rehydration cycles (Slate et al. 2019) which would be more frequent in Spring. This explanation is plausible, but incomplete.

Might mosses enhance NO_3^- loss through uptake? Contrary to long-standing assumptions, mosses can obtain mobile nutrients from soil (Ayres et al. 2006), and they require an N supply like all plants. Because mosses may be more active in the winter relative to other N consumers (e.g. vascular plants [Glime 2017], microbes [Pietikäinen et al. 2005]), we might expect a strong moss control on uptake at this time. In spring, many more N consumers would be actively growing, thus we might expect a weaker control of mosses on NO_3^- uptake because they are experiencing competition for N. If this explanation is true, the moss tissues are storing the "missing" N in organic forms. This explanation seems the most likely and is consistent with all observed patterns.

We cannot definitively rule out that another factor that happens to correlate with moss cover is the true driver of NO_3^- change. For example, insolation might be a factor underlying and influencing both moss cover (Durham et al. 2018, Grover et al. 2020) and NO_3^- loss by modifying the environment. However, moss cover is in fact the strongest overall correlate with NO_3^-, suggesting that the mosses are at least part of the story. With regards to NH_4^+, we can only conclude that inputs and outputs maintain a similar balance regardless of moss cover or season. It is possible that some NH_4^+ inputs or outputs are affected by mosses, but our data cannot detect these changes.

In summary, mosses appear to have a strong effect on the most mobile and preferred N source for most plants and microbes. To fully understand why will require a different kind of study capable of measuring the individual NO_3^- inputs and outputs. Regardless of the mechanism, mosses are clearly important to the fertility of soils in the post-fire landscape and should be better understood. If indeed mosses consume and draw down soil surface nitrogen in the post-fire landscape proportionally to their cover, this effect could have both positive and negative implications for land management. On one hand, mosses may compete with re-establishing plants for nitrogen. We have little direct evidence that this is happening, however. Vascular plants cover and moss cover do not appear to correlate, positively or negatively. On the other hand, mosses may retain and protect the site's N from losses caused by leaching or erosion. Over the long-term, this may mean that a larger quantity of the original pre-fire N pool remains in the site and may be re-mineralized upon the death of mosses. Retaining NO_3^- on site would hypothetically protect surface water quality by reducing enhancement of nutrient loads commonly observed in association with fire (Baldon et al. 2020). Any effect of mosses on nitrogen in the post-fire environment would also have to be weighed against likely improvement of soil aggregate stability, and possible improvement of hydrological function (Grover et al. 2020, Silva et al. 2019).

Objective 4: Disseminate information to BAER practitioners and the research community

- We presented results from this grant and ongoing dissertation work at two regional and one international conference using JFSP funding. The 2019 8th International Fire Ecology and Management Congress (Talk), The 2019 Society for Ecological Restoration Southwest Conference (Invited Talk), and the 2019 Biennial Conference of Research and Management on the Colorado Plateau (Invited Talk).
- We assisted in an effectiveness monitoring effort to examine how straw and wood mulching affected postfire sediment yield. This work involved collaboration with Jason Jimenez and nine members of the Colville National Forest soils crew. This involved field work, statistical analysis, and co-authoring a final report.

1. Report: Toledo K, Grover HS, Kvamme C, Jimenez J, Stickpin Fire BAER implementation – Colville National Forest level II effectiveness monitoring final report. 2019

- We presented results from this report cited above at a BAER regional coordinator meeting in March of 2019.
- We presented a webinar and created a fact sheet outlining growing fire moss, field trials of greenhouse grown fire moss additions to burned areas, and a survey of fire moss natural colonization and function in the Southwestern US. Both deliverables are available on the Southwest Fire Science Consortium Website.

1. Webinar: Grover HS, Bowker MA, Fulé PZ. Fire Moss: An understudied phenomenon and potential tool for post-fire rehabilitation. Southwest Fire Science Consortium Website. April 2020.
2. Factsheet: Grover HS, Bowker MA, Fulé PZ. Fire Moss: Natural colonization and post-fire rehabilitation trials. Southwest Fire Science Consortium Website. April 2020.

- We attempted to present research results to land managers via a BAER team leader workshop in spring 2020, but this was canceled due to the Covid-19 pandemic.

5. Conclusions, Management/Policy Implications, and Future Research:

We found that postfire moss cover was inhibited by wood shred mulch, straw mulch, and litter cover in this study system. In fact, fire moss preferentially colonized bare soil and could complement mulch as effective living ground cover that colonizes rapidly after a wildfire. Fire mosses have been shown to reduce erosion but not runoff in 1x1m plots in a recently burned environment (Silva et al. 2019), but future research is necessary to understand how effective moss cover is compared to mulching treatments. Research is currently underway to better quantify the speed and location of fire moss recolonization after wildfires in the northwestern US.

We also found that postfire logging can both reduce and increase moss cover on skid trails when compared to undisturbed postfire hillslopes. Skid trails are the largest sources of postfire runoff and erosion in salvage logging operations and moss may provide valuable cover in these areas if it does colonize (Robichaud, Lewis, et al. 2020). Future work should focus on understanding the drivers of moss colonization on skid trials and exploring the potential for active skid trial restoration using fire mosses.

Finally, we explored the impacts of fire moss colonization on nitrogen availability to plants. Moss cover did not affect ammonia (NH_4^+) availability but was inversely related with nitrate (NO_3^-) availability, especially during the winter vascular plant dormancy phase vs the spring active phase. We hypothesize, this is due to uptake of NO_3^- by mosses throughout the winter but this should be studied in more detail. Moss uptake of NO_3^- could reduce vascular plant growth in the short term if nitrogen is limiting however it could also reduce nitrogen loss via leaching and runoff to surface water during spring snowmelt. In general, postfire moss colonization has not been studied in detail and many open avenues for future research still exist. What results do exist point to fire moss's ability to colonize burned areas rapidly and contribute to the recovery of these ecosystems.

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Appendix A: Contact information for Key Project Personnel

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Completed

Dissertation:

Grover HS. Fire Moss: An understudied phenomenon and potential tool for post-fire rehabilitation. April 2020.

Publications:

Grover HS, Bowker MA, Fulé PZ, Doherty KD, Sieg CH, Antoninka AJ. 2020. Post-wildfire moss colonization and soil functional enhancement in forests of southwestern USA. *International Journal of Wildland Fire*. https://doi.org/10.1071/WF19106

Toledo K, Grover HS, Kvamme C, Jimenez J, Stickpin Fire BAER implementation – Colville National Forest level II effectiveness monitoring final report. 2019

Presentations:

Grover HS**,** Bowker MA, Fulé PZ, Sieg CH, Doherty KD, Antoninka AJ. Active and passive rehabilitation of fire mosses in severely burned forests of the southwestern US. 8th International Fire Ecology and Management Congress. Association for Fire Ecology. Flagstaff, Arizona, November 2019. (Talk)

Grover HS**,** Bowker MA, Fulé PZ, Sieg CH, Doherty KD, Antoninka AJ. Active and passive rehabilitation of fire mosses in severely burned forests of the southwestern US. Society for Ecological Restoration Southwest. Tucson, Arizona, November 2019. (Invited Talk)

Grover HS**,** Bowker MA, Fulé PZ, Sieg CH, Doherty KD, Antoninka AJ. Active and passive rehabilitation of fire mosses in severely burned forests of the southwestern US. Biennial Conference of Research and Management on the Colorado Plateau. Flagstaff, Arizona, September 2019. (Invited Talk)

Grover HS**, (**Presented by) Bowker MA, Fulé PZ, Sieg CH, Antoninka AJ. Pelletizing and grinding increase moss establishment in severely burned conifer forests of the Southwestern USA. Biocrust 4. North Stradbroke Island (Minjerrabah), Queensland, Australia. August 2019 (Talk)

Grover HS**,** Toledo K, Kvamme C, Jimenez J. BAER Stickpin Level II Aerial Mulching Effectiveness Monitoring. BAER regional coordinators meeting. April 2019. (Talk)

Factsheet:

Grover HS, Bowker MA, Fulé PZ. Fire Moss: Natural colonization and post-fire rehabilitation trials. Southwest Fire Science Consortium Website. April 2020.

Webinar:

Grover HS, Bowker MA, Fulé PZ. Fire Moss: An understudied phenomenon and potential tool for post-fire rehabilitation. Southwest Fire Science Consortium Website. April 2020.

In Prep

Publications:

Grover HS, Bowker MA, Fulé PZ, Sieg CH, Antoninka AJ. Pelletized inoculation overcomes ant predation and enhances fire moss establishment in severely burned conifer forests.

Grover HS, Bowker MA, Fulé PZ, Sieg CH, Toledo K, Jimenez J, Robichaud PR. The effects of postfire mulching and salvage logging on bryophyte cover and soil nutrients.

Grover HS, Bowker MA, Fulé PZ, Sieg CH, Jimenez J, Robichaud PR. Post-wildfire moss colonization in forests of the Northwestern USA. *International Journal of Wildland Fire.*

Appendix C: Metadata

Data and metadata will be made publicly available at the Forest Service Research Data Archive (www.fs.usda.gov/rds/archive) using the FGDC Biological Data Profile (BDP) standard. Data will include plot locations, treatment types, all cover values taken, and plant available nutrients. Both cover data collection and nutrient data collection methods were updated from the original data management plan to reflect a new, more robust sampling design implemented after project funding.