The relationship between tree-removal treatments and soil hydrophobicity in woodland encroached sagebrush ecosystems

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Abstract

1 Introduction and Background

The sagebrush ecosystem is one of the most at-risk ecosystems in the United States. Sagebrush ecosystem degradation has mostly been attributed to human disturbances, invasive plants, and woody plant encroachment (Pierson et al. 2013), (Williams et al. 2020). One example of woody plant encroachment in the sagebrush ecosystem is the encroachment of pinyon and juniper woodlands. Pinyon and juniper encroachment have several ecological impacts on sagebrush ecosystem degradation, one such being the impact on soil erosion and soil hydrophobicity (Glenn & Finley 2010), (Pierson et al. 2014).

These hydrological impacts in sagebrush ecosystems are attributed to the change in vegetation structure and alterations in the ecosystem's fire regime. Soil hydrophobicity is one hydrologic characteristic that is influenced by these changes. Hydrophobicity is often the result of hydrophobic compounds from plants making their way into the soil and can happen due to fire, but also without fire due to leaching from plants and other sources (Pierson et al. 2008). Glenn & Finley (2010) found that, in a sagebrush ecosystem, moderate severity fire led to the most hydrophobicity. Meanwhile, Pierson et al. (2008) found that fire itself had little effect on hydrophobicity and that climatic conditions were more responsible for hydrophobicity across both prescribed and wildfires in sagebrush. It is important to note that the ecosystem studied in this analysis is woodland encroached sagebrush with significant populations of pinyon and juniper. Zvirzdin et al. (2017) found significant post-fire soil hydrophobicity under the canopy of pinyon and juniper.

Restoration efforts aiming to improve soil erosion in sagebrush ecosystems are focused on counteracting woodland encroachment to revert vegetation structure and improve overall site resilience to encroaching woodlands. Despite the increase of research in post-fire soil hydrophobicity in sagebrush ecosystems over the last two decades, there remains questions concerning the hydrological effects on different types of tree-removal treatments. This analysis seeks to clarify the effect of tree-removal treatments and fire on soil hydrophobicity in a woodland-encroached sagebrush ecosystem.

2 Methods

This data was collected as part of the Sagebrush Steppe Treatment Evaluation Project by Williams, C. J., Pierson, F. B., Kormos, P. R., Al-Hamdan, O. Z., and Johnson, J. C. (Williams et al. 2020). Sites were located within the Great Basin in areas that were historically sagebrush dominated but have become pinyon and juniper woodlands. Sites were treated with a variety of tree removal treatments, including cutting, masticating, prescribed fire, and wildfire. Observations were recorded in some cases before treatment, 1 and 2 years after treatment at all plots and 9 years after treatment at some plots. Experiments were run at multiple scales. This analysis focused on small plots (0.5 m^2) (n=528). A variety of site characteristics were also recorded. Ground and shrub cover measurements were taken using a point intercept method. The study conducted the water drop penetration time test, a measure of soil hydrophobicity. In this test, a drop of water is placed on the soil and the time it takes to infiltrate is recorded. Recording was stopped after 300 seconds (5 minutes). 8 water drops were used and the average time for the plot at that depth was recorded. This test was done at the soil surface and repeated each centimeter to a depth of 5cm. This analysis uses only the measurements from the surface as previous studies indicate there is little evidence of hydrophobicity deeper than 2cm (Glenn & Finley 2010).

3 Data Preparation and Statistical Analysis Methods

Data cleaning and preparation was performed. Multiple variables had to be created or modified. A new treatment type variable was created to better represent the data. In the raw data, observations were categorized as 'control', 'cut', 'bullhog', 'burn', and 'unburned'. Burned plots were divided into 'wildfire' and 'Rx' (prescribed fire) based on location. A description of which locations received wildfire or prescribed fire is present in (Williams et al. 2020). Unburned plots and observations of plots prior to treatment were categorized as 'Control'. This led to a high number of 'Control' observations (n= 262).

The water drop penetration time data was highly skewed, with many plots having a time of 3 seconds, the shortest possible time (n= 370 of 514). The data was natural log transformed for analysis. While this did not remove the problem of so many minimum observations, it did normalize the rest of the data. Due to the non-normality of the data, for regression modelling the water penetration time data was broken into binary groups with no hydrophobicity, 'Non-Hydrophobic' (water drop penetration time = 3s), and some level of hydrophobicity, 'Hydrophobic' (water drop penetration time $>$ 3s).

An additional variable `burned_unburned` was created to analyze the relationship of fire to hydrophobicity. Treatments using fire (Rx and Wildfire) were considered burned and all other treatments including control were considered unburned.

To answer the question of how tree-removal treatments affect soil hydrophobicity an ANOVA test was performed on the variables of log of surface soil water penetration time and treatment type. The alternate hypothesis was that at least one treatment type would be significantly different. This was found to be significant so a Tukey HSD post-hoc test was performed to determine which relationships were significant.

Table 1: Sample characteristics of data used in analyses.

Variable	**N = 528**[1]
ANOVA	
Log Surface Soil Water Penetration Rate	1.91 (1.49)
Missing	14
Treatment Type	
Bullhog	70/528 (13%)
Control	262/528 (50%)
Cut	38/528 (7.2%)
Rx	118/528 (22%)
Wildfire	40/528 (7.6%)
Logistic Regression Model	
Hydrophobicity	
Non-Hydrophobic	370/514 (72%)
Hydrophobic	144/514 (28%)
Missing	14
Mean Litter Depth (cm)	1.32 (2.25)
Missing	10
Foliage Shrub Cover	10 (22)
Bare Soil Ground Cover	31 (23)
Burn Treatment	
Burned	158/528 (30%)
Unburned	370/528 (70%)

[1]Mean (SD); n/N (%)

A multiple regression analysis was performed to determine the relationship between hydrophobicity and burn treatments, using the binary hydrophobicity and burn treatment variables. Due to the binary nature of the response variable, hydrophobicity, a logistic regression model was used. Additional predictor variables used in the model include litter depth in centimeters, percentage of the plot that was bare ground, and percentage of the plot with shrub cover. These three variables affect both surface exposure and also soil stability and compaction which may have an influence on hydrophobicity.

4 Results

The p-value of the ANOVA test of log surface soil water penetration time and treatment type is small (p=0.036), so there is evidence to support the hypothesis that at least one group mean is different.

There is sufficient evidence to believe that the mean is significantly different between wildfire and control treatments (p=0.048). The results of the Tukey HSD post-hoc test indicate that the log surface soil water penetration rate is significantly different between wildfire and control treatments at the 5% significance level, with wildfire treatment's average log surface soil water penetration rate being 0.69 (0.03. 1.38) less than control treatments.

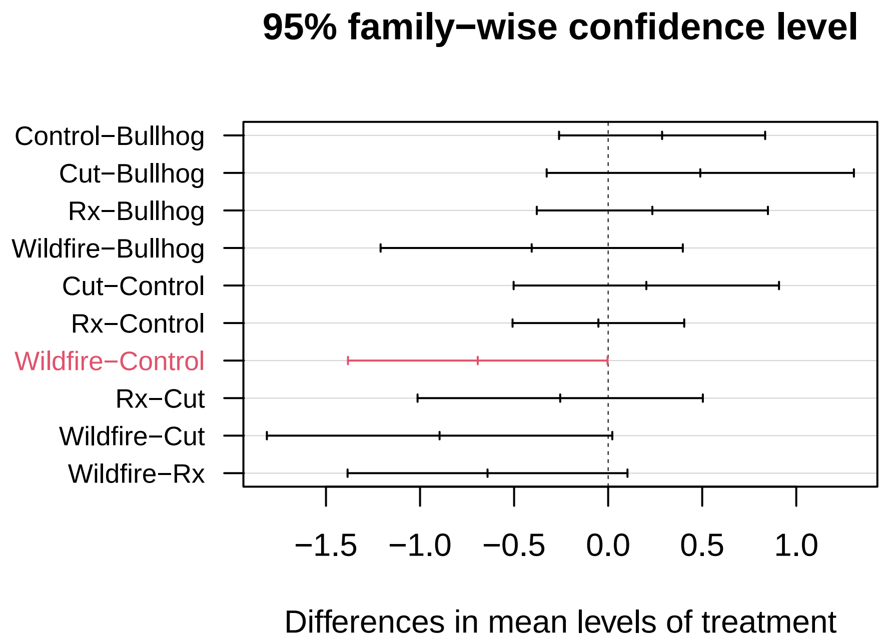

Figure 1: Results of the Tukey HSD post-hoc test showing the significant difference between Wildfire and Control treatments.

Logistic Regression Model

The predicted probability for a plot with a burn treatment, a litter depth, bare soil ground cover, and shrub foliage cover of 0 to have hydrophobic soil is 0.96% (95% CI 0.43, 2.14). This is not a significant association (p=0.91).

After controlling for plot-treatment, bare soil ground coverage and shrub foliage cover, every additional centimeter of litter depth is associated with a 1.58 times the odds that a plot has hydrophobic soil (95% CI 1.31, 1.94).This is a significant association (p<0.001).

After controlling for plot-treatment, litter depth and shrub foliage cover, every additional percentage point of bare soil ground cover is associated with a 0.96 times the odds that a plot has hydrophobic soil (95% CI 0.94,0.98).This is a significant association (p<0.001).

After controlling for plot-treatment, litter depth and bare soil ground cover, every addi-

Table 2: Logistic Regression Model Results

Characteristic	**OR**[1]	**95% CI**[1]	**p-value**
(Intercept)	0.96	0.43, 2.14	>0.9
Mean Litter Depth (cm)	1.58	1.31, 1.94	**<0.001**
Bare Soil Ground Cover	0.96	0.94, 0.98	**<0.001**
Foliage Shrub Cover	0.98	0.96, 0.99	**0.008**
Treatment Status			
Burned	—	—	
Unburned	0.58	0.32, 1.04	0.070

[1]OR = Odds Ratio, CI = Confidence Interval

tional percentage point of shrub foliage cover is associated with a 0.98 times the odds that a plot has hydrophobic soil (95% CI 0.96,0.99).This is a significant association (p=0.008).

After controlling for litter depth, bare soil ground cover and shrub foliage cover, non-burned treatments is associated with a 0.58 times the odds that a plot has hydrophobic soil (95% CI 0.32,1.04).This is not a significant association (p=0.07).

This model correctly predicts whether or not a plot had some measure of hydrophobicity 77.4% of the time.

Models with individual treatment types were considered. Theses models produced similar results to the chosen model with no significance of treatment type. Due to small sample sizes for some treatments ($N_{\text{cut}} = 38$, $N_{\text{Rx}} = 40$) these models were not used for the study due to lack of robustness.

5 Discussion and Conclusion

Our results showed that wildfire had the most significant effect on hydrophobicity. Wildfire treatment's average log water penetration time at the surface soil was significantly less than control treatments ($p<0.05$). This is potentially due to the impacts that moderate to high severity fire has on loosening the soil and clearing the ground. However, the ANOVA results should be interpreted with some caution. The water penetration time data was highly skewed, violating several assumptions. Additionally, some treatment types had very small sample sizes ($N_{cut} = 38$, $N_{Rx} = 40$) leading to more room for error.

When confounding factors were evaluated, the relationship between fire and hydrophobicity did not remain significant ($p_{unburned} = 0.07$). This is interesting given that some previous studies found that burning was predictive of soil hydrophobicity in this ecosystem (Glenn & Finley 2010), (Zvirzdin et al. 2017). We found that instead of fire, factors such as shrub cover and bare ground had a significant effect on the hydrophobicity ($p= .008$, $p<.001$ respectively). (Pierson et al. 2008) found similar results, with site characteristics being more important than presence of fire. It is possible that these factors were not taken into account in studies that found significant changes due to fire. Fire is also a very dynamic and spatially heterogeneous process that is highly dependent on pre-fire vegetation conditions and factors such as weather. Specific fire conditions may have influenced hydrophobicity but were unable to be analyzed in this study.

An additional confounding factor is that fire changes plot characteristics that we found to have a significant effect on hydrophobicity, such as litter depth. How fire itself changes soil hydrophobicity compared to how fire changes other factors that influence hydrophobicity is an avenue for further research.

This analysis also did not look at the specific plant species present on the plots. Different species affect the hydrophobicity of the soil around them (Zvirzdin et al. 2017). This could have influenced our results and in particular may have contributed to the significance of shrub cover as a predictive factor of hydrophobicity. Further research is needed to explore the effect specific species have on hydrophobicity in sagebrush ecosystems.

An significant limition of this analysis is the repeated observation of plots. It is possible that the ultimately connected nature of these plots, with most plots sampled more than once but treated in this analysis as separate, was highly influential and favored some factors over others.

The results of this study are only generalizable to sagebrush ecosystems or other ecosystems with similar fuel characteristics and climate. Ecosystems with different fuel types and spacing will respond differently to fire and thus the results cannot be generalized to them. Even though these results are only applicable to specific ecosystems, the management of said ecosystems is an ongoing concern. These results inform an important part of understanding management effects on woodland encroached sagebrush ecosystems, particularly that characteristics created by treatments may have a greater impact than the treatment type that produced them.

6 Disclosure statement

The authors declare that no conflicts of interest exist.

7 Data Availability Statement

Data have been made available at the following URL: https://doi.org/10.15482/USDA.ADC/1504518

8 Code Appendix

```
# Load libraries
library(sjPlot); library(ggplot2); library(ggpubr); library(gtsummary);
library(performance); library(dplyr); library(hrbrthemes); library(viridis);
library(RColorBrewer); library(ggdist)
```

```
load(here::here('Data/smallplots_clean.Rdata'))
```

Data Preparation and Analysis

```
Sampchar1 <- smallplots_clean |> select(log_wpt_0cm,treatment)


Sampchar1 <- Sampchar1 %>% rename("Treatment Type" = treatment)
Sampchar1 <- Sampchar1 %>% rename("Log Surface Soil Water Penetration Rate" =
                                  log_wpt_0cm)


Sampchar2 <- smallplots_clean |> select(binned_wpt_0cm, lit_depth_cm,
                                 fol_cvr_shrub,  grd_bare_soil, burned_unburned)
```

```
Sampchar2 <- Sampchar2 %>% rename("Hydrophobicity"= binned_wpt_0cm)

Sampchar2 <- Sampchar2 %>% rename("Mean Litter Depth (cm)" = lit_depth_cm)

Sampchar2 <- Sampchar2 %>% rename("Foliage Shrub Cover" = fol_cvr_shrub)

Sampchar2 <- Sampchar2 %>% rename("Bare Soil Ground Cover" = grd_bare_soil)

Sampchar2 <- Sampchar2 %>% rename("Burn Treatment"= burned_unburned)
```

```
tbl1<- Sampchar1 |> tbl_summary(statistic = list(

        all_continuous() ~ "{mean} ({sd})",

        all_categorical() ~ "{n}/{N} ({p}%)"),

        missing_text = "Missing") %>%

    bold_labels() %>%

    italicize_levels()


tbl2<- Sampchar2 |> tbl_summary(statistic = list(

        all_continuous() ~ "{mean} ({sd})",

        all_categorical() ~ "{n}/{N} ({p}%)"),

        missing_text = "Missing") %>%

    bold_labels() %>%

    italicize_levels()


tbl_stack(list(tbl1, tbl2), group_header = c("ANOVA",

                                             "Logistic Regression Model")) %>%

  modify_header(label ~ "**Variable**") %>%

  modify_caption("Table 1")
```

Table 3: Sample characteristics of data used in analyses.

Variable	**N = 528**[1]
ANOVA	
Log Surface Soil Water Penetration Rate	1.91 (1.49)
Missing	14
Treatment Type	
Bullhog	70/528 (13%)
Control	262/528 (50%)
Cut	38/528 (7.2%)
Rx	118/528 (22%)
Wildfire	40/528 (7.6%)
Logistic Regression Model	
Hydrophobicity	
Non-Hydrophobic	370/514 (72%)
Hydrophobic	144/514 (28%)
Missing	14
Mean Litter Depth (cm)	1.32 (2.25)
Missing	10
Foliage Shrub Cover	10 (22)
Bare Soil Ground Cover	31 (23)
Burn Treatment	
Burned	158/528 (30%)
Unburned	370/528 (70%)

[1] Mean (SD); n/N (%)

Results

```
anova<- aov(log_wpt_0cm ~ treatment, data=smallplots_clean)

tukey<- TukeyHSD(aov(log_wpt_0cm ~ treatment, data=smallplots_clean))

summary(anova)
```

```
             Df Sum Sq Mean Sq F value Pr(>F)
treatment     4   22.7   5.681   2.592 0.0359 *
Residuals   509 1115.6   2.192
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
14 observations deleted due to missingness
```

```
tukey
```

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = log_wpt_0cm ~ treatment, data = smallplots_clean)

$treatment
                       diff        lwr          upr     p adj
Control-Bullhog   0.28681621 -0.2609829  0.834615283 0.6063646
Cut-Bullhog       0.48977360 -0.3268571  1.306404321 0.4712914
```

```
Rx-Bullhog        0.23491944 -0.3794684  0.849307230 0.8333762
Wildfire-Bullhog -0.40635751 -1.2096468  0.396931786 0.6376955
Cut-Control       0.20295739 -0.5025067  0.908421483 0.9341803
Rx-Control       -0.05189678 -0.5082587  0.404465161 0.9979585
Wildfire-Control -0.69317373 -1.3831502 -0.003197237 0.0483036
Rx-Cut           -0.25485416 -1.0131866  0.503478305 0.8891504
Wildfire-Cut     -0.89613111 -1.8142103  0.021948116 0.0595708
Wildfire-Rx      -0.64127695 -1.3852232  0.102669349 0.1282214
```

```r
TukeyWPT <- TukeyHSD(aov(log_wpt_0cm ~ treatment, data=smallplots_clean))
psig=as.numeric(apply(TukeyWPT$`treatment`[,2:3],1,prod)>=0)+1
op=par(mar=c(4.2,9,3.8,2))
plot(TukeyWPT,col=psig,yaxt="n")
for (j in 1:length(psig)){
  axis(2,at=j,labels=rownames(TukeyWPT$`treatment`)[length(psig)-j+1],
     las=1,cex.axis=.8,col.axis=psig[length(psig)-j+1])
}
```

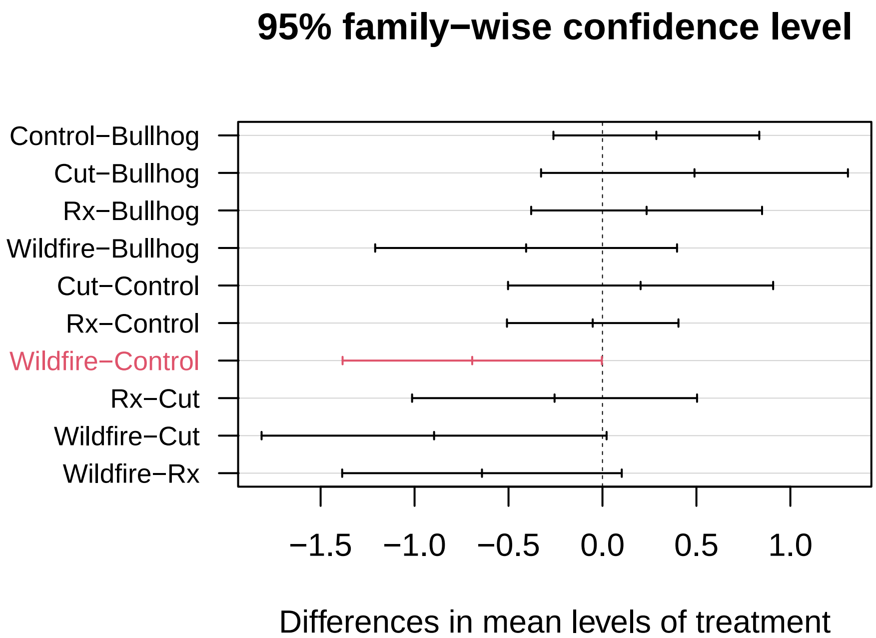

Figure 2: Results of the Tukey HSD post-hoc test showing the significant difference between Wildfire and Control treatments.

Code from (JoshM8 2015).

```
model3 <- glm(binned_wpt_0cm ~ lit_depth_cm + grd_bare_soil + fol_cvr_shrub +
                burned_unburned, data=smallplots_clean, family='binomial')


tbl_regression(model3, exponentiate = TRUE, intercept = TRUE,
  label = list(lit_depth_cm ~ "Mean Litter Depth (cm)",
               grd_bare_soil ~ "Bare Soil Ground Cover",
               fol_cvr_shrub ~ "Foliage Shrub Cover",
               burned_unburned ~ "Treatment Status")) |>
  bold_labels() |>
  bold_p() |>
```

Characteristic	OR[1]	95% CI[1]	p-value
(Intercept)	0.96	0.43, 2.14	>0.9
Mean Litter Depth (cm)	1.58	1.31, 1.94	**<0.001**
Bare Soil Ground Cover	0.96	0.94, 0.98	**<0.001**
Foliage Shrub Cover	0.98	0.96, 0.99	**0.008**
Treatment Status			
Burned	—	—	
Unburned	0.58	0.32, 1.04	0.070

[1]OR = Odds Ratio, CI = Confidence Interval

```
  italicize_levels()
```

```
model_performance(model3, metrics = "PCP")
```

```
# Indices of model performance

PCP
-----
0.774
```

References

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