The Re-Establishment of a Ponderosa Pine Forest: a Multiple-Scale Twenty-year Retrospect of the Waldo Canyon Fire, Colorado

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Abstract:

In recent decades, the number of forest fires occurring in the western United States has significantly increased in response to fire suppression and climate change. As anthropogenic warming continues, wildfires are expected to increase in severity and size. The Rocky Mountain West is particularly vulnerable to these changes in climate conditions. Long periods of drought and rising temperatures across most elevations have been correlated with an increase in wildfire occurrence. Global warming in the West is predicted to create a shift from an infrequent, high severity fire regime to a novel fire regime in which high severity fires burn more often and affect larger areas . Historically, the fire regime of the Rocky Mountains is characterized as infrequent, low-to-moderate severity, and patchy. Scientists believe the shifting climate conditions may not support P. ponderosa dominated forests as fires increase in area burned, frequency and intensity. These high severity fires can be detrimental to forest types that have not historically experienced extreme fires, leading to a low likelihood of forest regeneration and the development of new post-fire ecological trajectories. P. ponderosa is poorly adapted to regenerate in large patches of high severity fire because of the of lack serotinous cones, the inability to maintain long-lived soil seedbanks, and shade-intolerance in the presence of flora that outcompete ponderosa pine in these conditions. Much of Colorado's Front Range, including the Waldo Canyon, have historically been dominated by ponderosa pine forests. This summer, we conducted a demographic study of ponderosa pine populations in the Waldo Canyon burn scar over 20 years after the fire occurred. In this study, we attempt to predict the Waldo Canyon landscape post 2020 fires by analyzing the presence or absence of P. ponderosa on north versus south facing slopes.

Introduction:

In recent decades, the number of forest fires occurring in the western United States has significantly increased as an outcome of modern human alteration of historic fire regimes and climate change (Chapman et al ., 2020) . As anthropogenic warming continues, wildfire trends are expected to increase in severity and size (Chapman et al ., 2020) . More specifically, global warming is anticipated to cause a shift from infrequent, high severity fire regimes to fire regimes in which scientists predict fire rotations to be less than 10 years apart by 2070-2099 (Westerling et al. , 2011). A transition to shrubland or non-forest ecosystems is the expected successional outcome of the change in fire frequency in these systems if trees cannot regenerate under more frequent and severe fire conditions (Haffey et al ., 2018).

One area specifically vulnerable to these changes is the Rocky Mountain West, where long periods of drought and rising temperatures across most elevations have been correlated with an increase in wildfire occurrence (Carter et al., 2019). The Rocky Mountain West is particularly vulnerable to these changes because long periods of drought and rising temperatures across most elevations have been correlated with an increase in fire occurrence. In this region of the United States, pine forests have evolved with low severity fire regimes (Haffey et al., 2018). Low severity fires thin out surface fuels, eliminating competitors like Douglas fir and Rocky Mountain juniper (Carter et al., 2019). ponderosa pine forests have experienced unprecedented high severity fires (Rother & Veblen, 2017). In addition, with the introduction of fire suppression during the 20th century, ponderosa pine forests have grown increasingly dense, creating large stores of surface fuels that pave the way for these high severity crown fires.

ponderosa pine is poorly adapted to regenerate in large patches of high severity fire due to its lack of serotinous cones, inability to maintain long-lived soil seedbanks, and shade-intolerance in the presence of flora that can outcompete ponderosa pine in these conditions (Owen et al. 2020).

Much of Colorado's Front Range, specifically Waldo Canyon, has historically been dominated by ponderosa pine forests (Brown et al. 2015). Our study area is in the Pike National Forest where most of the Waldo Canyon fire occurred. The Waldo Canyon Fire burned over 18,000 acres and has significantly altered the ecological landscape of this region (Johnson et al. 2014). This landscape has traditionally been dominated by a range of piñon-juniper woodlands, ponderosa pine, and Douglas fir forests (Young &

Rust, 2012). The project we proposed aims to answer these questions: What is the predicted landscape post 2012 fires? Will ponderosa pine become “extinct” in some of the most severely burned forests? What species are returning? What does their presence or absence mean from a socio-ecological perspective? Is restoration recommended or should natural processes be allowed to unfold?

Study Area:

The Waldo Canyon fire occurred in Colorado’s Front Range in 2012 (Young & Rust, 2012; Figure 1). The burn has been categorized as 19% high severity, 40% moderate severity, and 41% low severity (Young & Rust, 2012; Figure 2). Our study area is in the Pike National Forest where much of the burn occurred. This region is dominated by piñon-juniper woodlands, ponderosa pine, and Douglas fir. Sites were located between 8,500 ft – 9,500 ft in elevation, 38°-39° longitude, and 104°-105° latitude.

Methods:

Site Selection:

Using ArcGIS Pro, we randomly generated points on north and south facing slopes in the Waldo Canyon’s Day 1 burn scar (Figures 4 and 5).

To access these potential sites, we drove Rampart Range Road through Pike- San Isabel National Forests , Woodland Park , Colorado to scout randomly assigned sample sites . During th e site selection process, we considered accessibility, terrain, length of slope, width of slope, and aspect of slope. Our aim was to lay a transect 500 meters in length from high to low elevations . After visiting numerous sites on both north and south facing slopes , we found laying a 500m transect would not be feasible in most of the selected sites because the slope distance of most sites measured less than 500m. To adjust, we shortened our transect length to 300m. Selected sites were those in which we could lay four 200m transects perpendicular to our 300m center line to create a grid of six 100m x 100m plots (Greig-Smith, 1983). If terrain inhibited our ability to lay a transect, we shifted our transect to proximal slopes that were more navigable. We then measured out 200m across the top and bottom of the slope to verify that the site matched our width requirement. In addition, we identified the bearing of the downslope. We added and subtracted ninety degrees to find the bearings of the East and West edges of our plots. With the center of the 300m transect laid, we measured out 100m east and west of the center transect, identified our bearings, and marked the points, creating our six 100 m x 100m plots. Overall, we laid seven transects on both north and south facing slopes, totaling 42 plots (Figure 6).

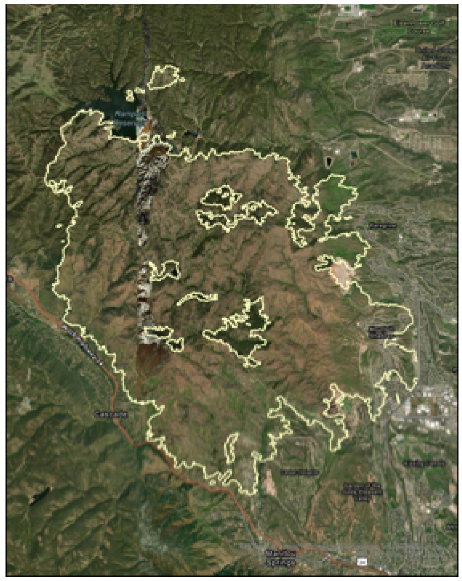


Figure 1. Map of Waldo Burn Area Perimeter, City of Colorado Springs, Final After Action Report, (2013). Map created in ArcGIS Pro v3.1 by Matt Cooney (2024).

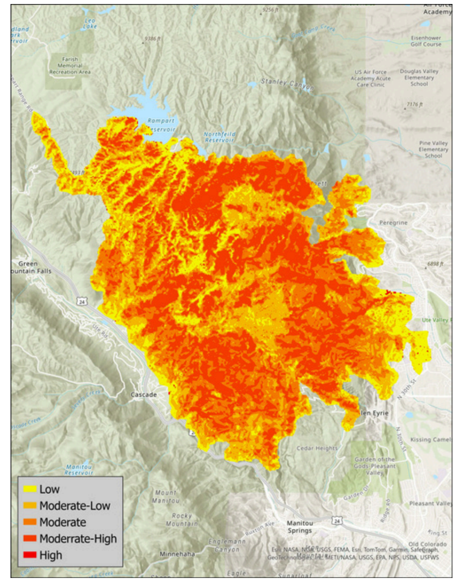


Figure 2. Predicted Burn Severity map of Waldo Canyon, Woodland Park, Colorado. Map adapted from Herros, A. (2018).

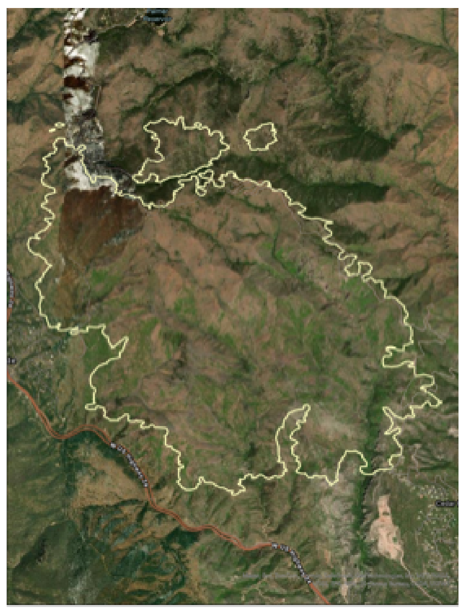


Figure 3. Waldo Canyon Burn Area Day 1, City of Colorado Springs, Final After Action Report, April 2013. Map created in ArcGIS Pro v3.1 by Matt Cooney (2024).

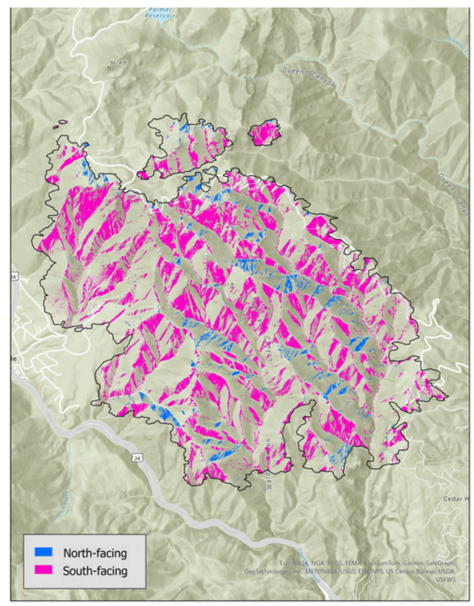


Figure 4. North and south identified slopes in burn day one area. Map created in ArcGIS Pro v3.1 by Matt Cooney (2024).

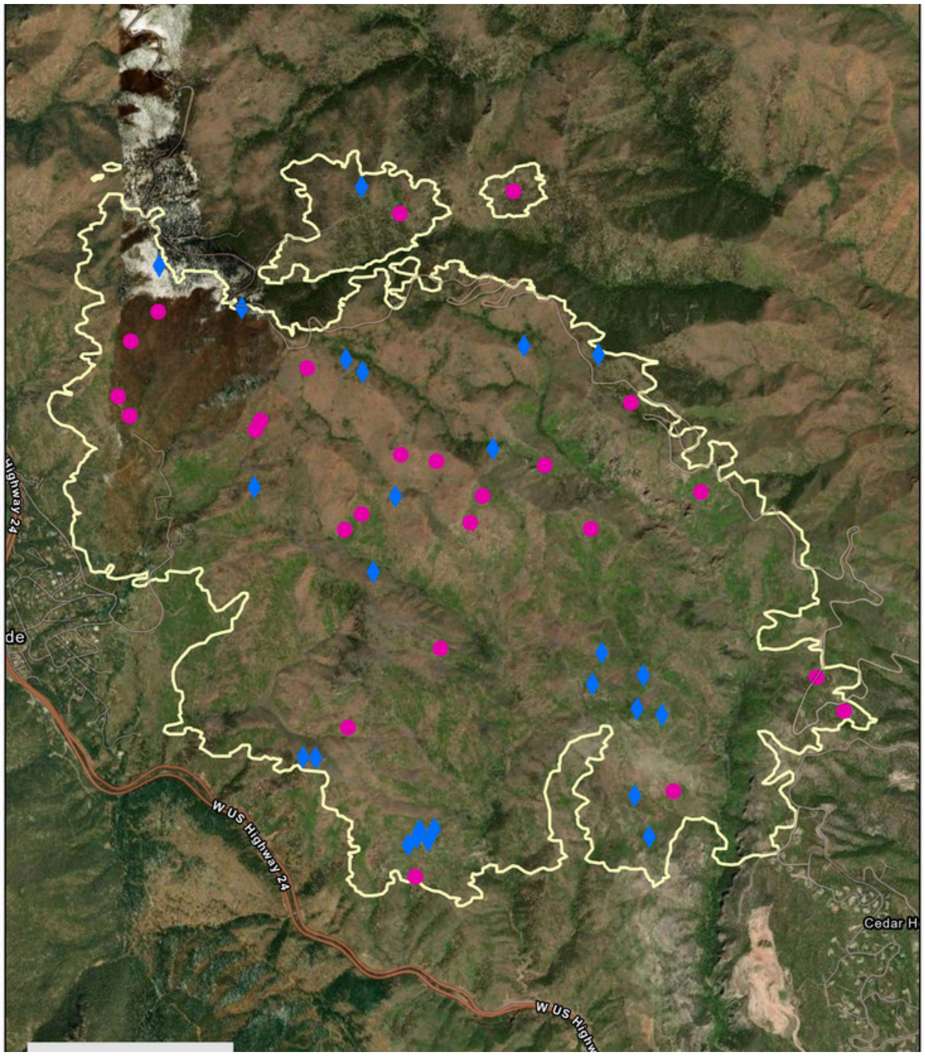


Figure 5. Randomly assigned points were generated and located within the burn day one area on north- and south-facing slopes. Study sites were then selected by visiting each point in chronological order (random point 1 visited first, then point 2, and so on) until five sites in each aspect (north and south) met our site criteria: accessibility, aspect, and within the burn area and national forest boundary. Map created in ArcGIS Pro v3.1 by Matt Cooney (2024).

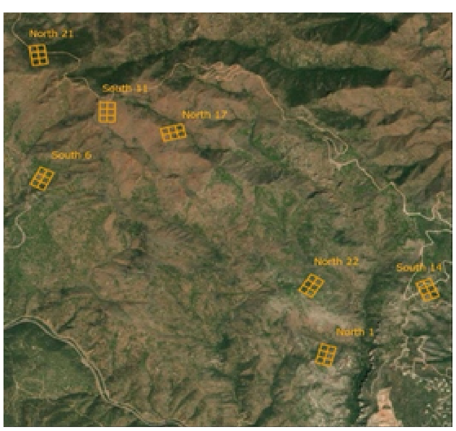


Figure 6. Study site locations of study plots on north and south-facing slopes within the Waldo Canyon burn day one area.

Data Collection:

Percent cover

Within each quadrant of each study site, we divided the quadrant into four 50m x 50m squares and estimated the amount of ground cover to the nearest percent. After estimating percent cover in each 50 m x 50 m plot, we averaged these numbers to determine the percent cover for the entire quadrant.

Ponderosa pine sapling presence

At our selected sites, we counted the number of ponderosa pine saplings present in each 100m x 100m quadrant along our transect. This gave us an estimate of the amount of regeneration that has occurred in each study site since the Waldo Canyon fire.

Ponderosa pine sampling:

Four living mature ponderosa pine trees were sampled in each 100m x 100m quadrant along the 300m transect in each site. We selected our trees by first locating the center of each quad and locating the four closest living ponderosa pines to our center point. Using stem size and height of each tree as proxies for age, we recorded diameter at breast height (DBH) of individuals taller than 1.52m (5 feet) using a DBH tape and measured tree height using an inclinometer. We cored trees if they were mature (above 1.52m tall). The selected living mature trees were cored to determine approximate age of trees in each site to determine the stand age of each site. Slope and aspect were recorded for each living tree to determine if aspect and slope at the individual scale accounted for the presence or absence of ponderosa pine individuals at the quad-scale. We compared the aspect and slope at the quad-scale to aspect and slope determined by GIS techniques for each site.

iNaturalist Data:

Link: State of the Rockies - Waldo Canyon · iNaturalist

We are also interested in documenting post-fire flora and fauna recovery in the Waldo Canyon area. We used iNaturalist to identify various species. iNaturalist is an online social network used to share biodiversity information and identify species using artificial intelligence and public responses. For our research, we created a project through iNaturalist that only allowed our team to add information on plant, insect, and bird species in our study area. During our time in the field, from June 2023 – August 2023, 120 observations were made on iNaturalist by our team. We identified a total of 78 species, mainly flora. Some of our most common species included ponderosa pine, whole leaf paintbrush, common yarrow, sticky geranium, fringed sagebrush, great plains yucca, mountain mahogany, and gamble oak.

Aerial Imagery & ArcGIS Pro:

After collecting the data, we used ArcGIS Pro to produce land cover and slope maps. Aerial imagery with a spatial resolution of 1 meter was acquired for 2011 (pre-fire) and 2023 (post-fire) to accurately digitize different land covers (Figures 7 and 8). Before analysis began, 300m by 200m grid polygons were geo-referenced onto our eight site locations to represent our transects on the ground. Within each of our 8 site locations, we identified and digitized areas of ground into five classifications: trees; shrubs; grass; rocks/bare ground; dense dead standing of trees. We carried out two methods to calculate land cover percentage at both the site level and quadrant level with the digitization of the five classifications. In addition, we used the slope geo-processing tool to calculate and depict the percent slope for all the transects to highlight the variability of slope between our north and south facing sites (Figures 9 and 10). One method allowed us to calculate the average slope percentage of each quadrant, and another assisted in visually representing across all our sites this variability in slope characteristic of the Waldo Canyon landscape.

Statistical Analyses:

We wanted to know whether Pinus ponderosa regeneration is occurring in the 12-year-old day one burn area and if so, what influences the likelihood of seeing seedlings and saplings across a range of physical site conditions in Waldo Canyon. We are also interested in whether burn severity of each quad is a predictor of seedling and sapling presence. Additionally, we explored whether there is a linear relationship among the number of saplings found per quad and the physical site characteristics we measured. We ran a logistic regression analysis to identify a potential relationship between the likelihood of seeing seedlings and saplings across and physical site conditions in Waldo Canyon. GLM logistic regressions were used to determine whether there is a linear relationship between the number of saplings in each quad and the physical site characteristics we measured.

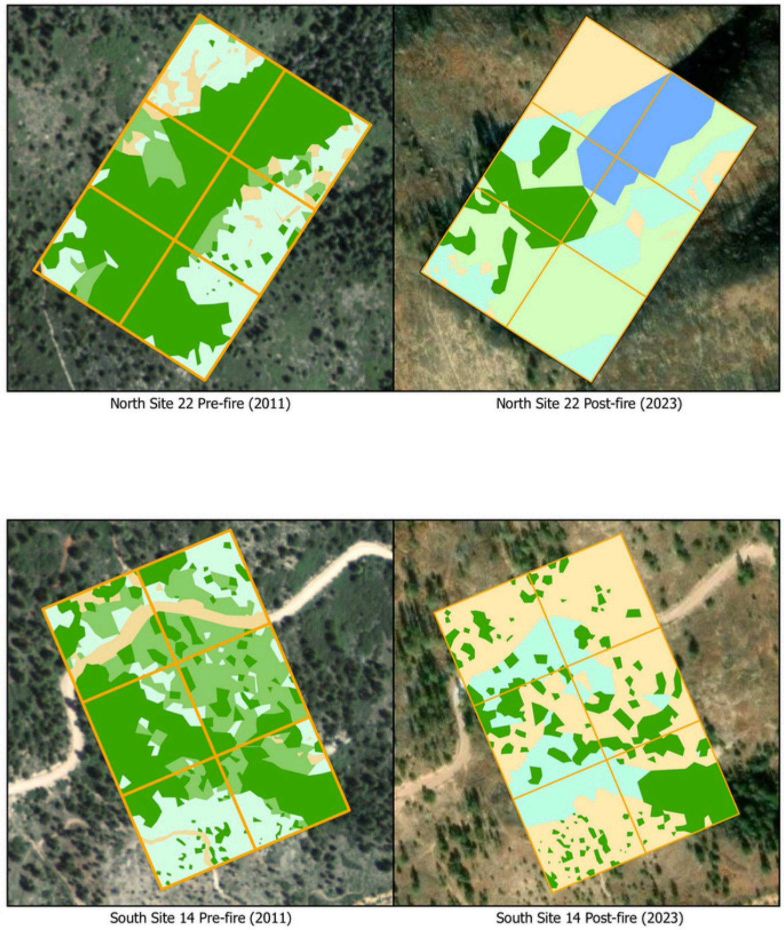
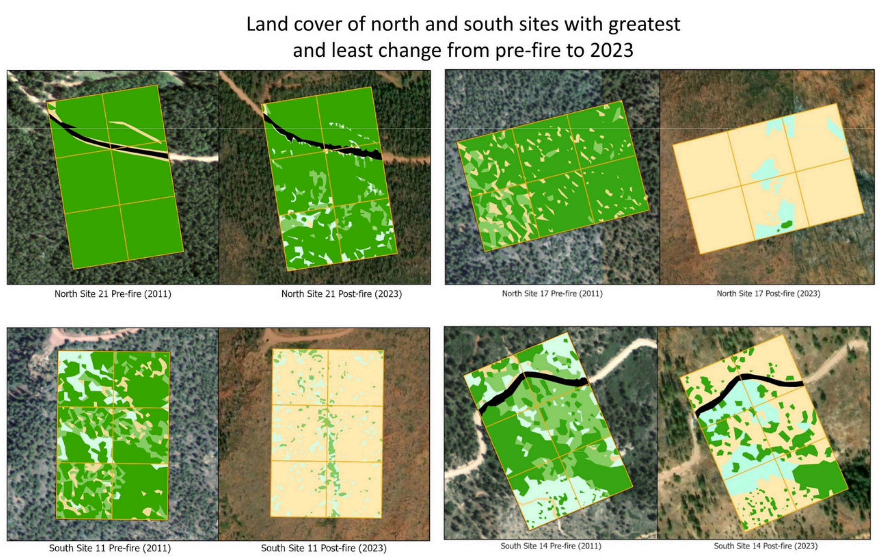


Figure 7. Digitized spacio-temporal changes in vegetation and land cover of pre- and post-fire conditions.



North 21	% Change
Trees	-12.17%
Shrubs	
Grass	
Rocks/bare ground	-75.79%
Roads	24.36%

South 11	% Change
Trees	-100%
Shrubs	-60%
Grass	-5%
Rocks/bare ground	911%

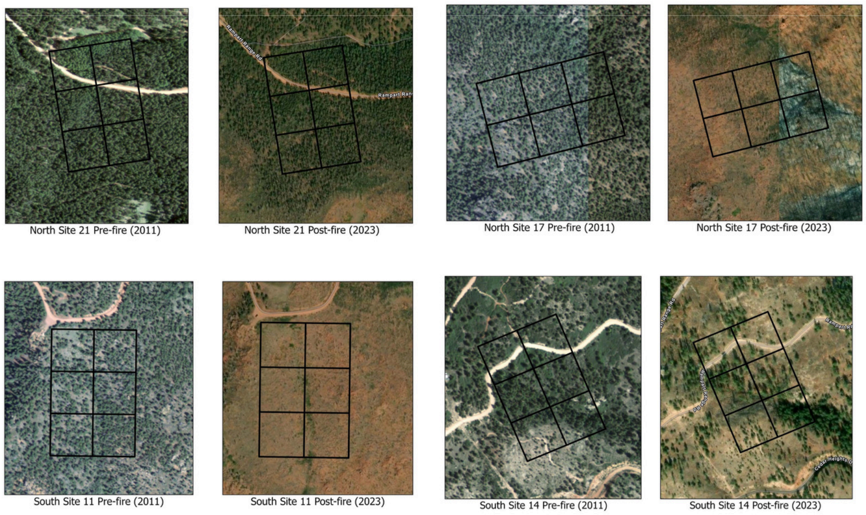
North 17	% Change
Trees	-100%
Shrubs	-100%
Grass	
Rocks/bare ground	798%

South 14	% Change
Trees	-41%
Shrubs	-100%
Grass	-10%
Rocks/bare ground	1800%
Roads	-15%

Note: blank data indicates no presence of that land cover in 2011 but is now present in 2023

Figure 8. Land cover of north and south sites with greatest and least change from pre-fire to 2023.

Aerial imagery comparison of north and south sites
of greatest and least change from pre-fire to 2023



The odds of seeing seedlings increases 1.325 with a one unit (%) increase in mean slope per quad (CI =95%). Quads ranged from a mean slope of 6.25% to 27.96%. The odds of seedlings and saplings being present increase 2.82 times with a one unit increase in mean elevation (meters) per quad (CI =95%). The mean elevation per quad ranged from 2215 meters to 2872 meters. We also conducted a logistic regression to analyze whether burn severity of each quad is a predictor of seedling and

A severely burned site in day one of the fire. | Photo by Cyndy Hines

South 6	% Change
Trees	-94%
Shrubs	125%
Grass	-46%
Rocks/bare ground	

South 11	% Change
Tree	-100%
Shrubs	-60%
Grass	-5%
Rocks/bare ground	911%

South 14	% Change
Trees	-41%
Shrubs	-100%
Grass	-10%
Rocks/bare ground	1800%
Roads	-15%

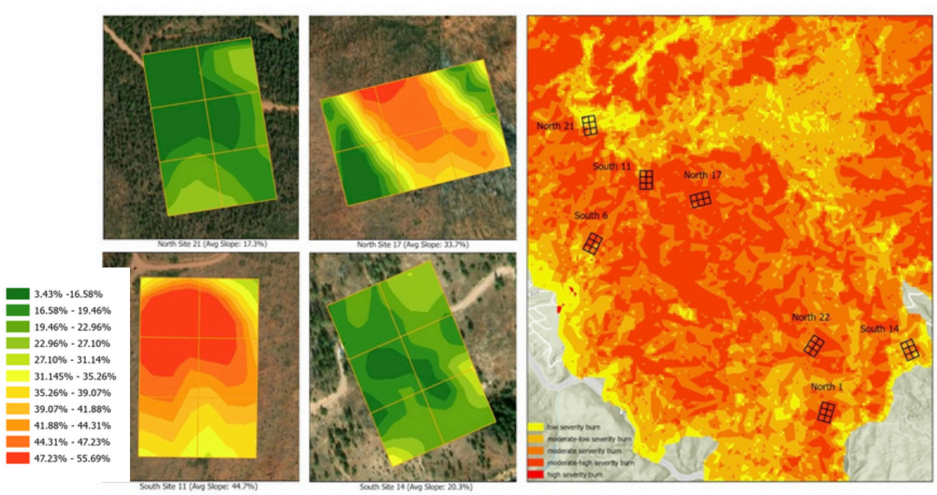
North 1	% Change
Trees	-94%
Shrubs	-59%
Grass	727%
Rocks/bare ground	201%

North 17	% Change
Trees	-100%
Shrubs	-100%
Grass	
Rocks/bare ground	798%

North 21	% Change
Trees	-12.17%
Shrubs	
Grass	
Rocks/bare ground	-75.79%

N22	% Change
Trees	-77%
Shrubs	365%
Grass	-32%
Rocks/bare ground	176%

Table 1. Percent of land cover changes in sample sites following fire (2011 to 2023).



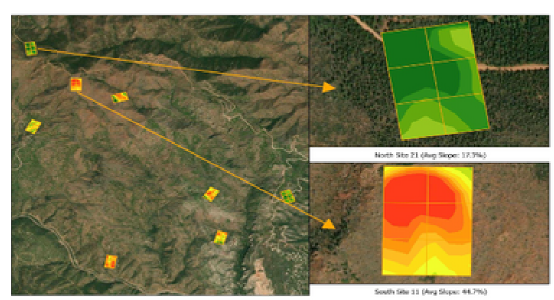


Figure 9. Slope percentage and locations of sites of varying degrees of burn severity.

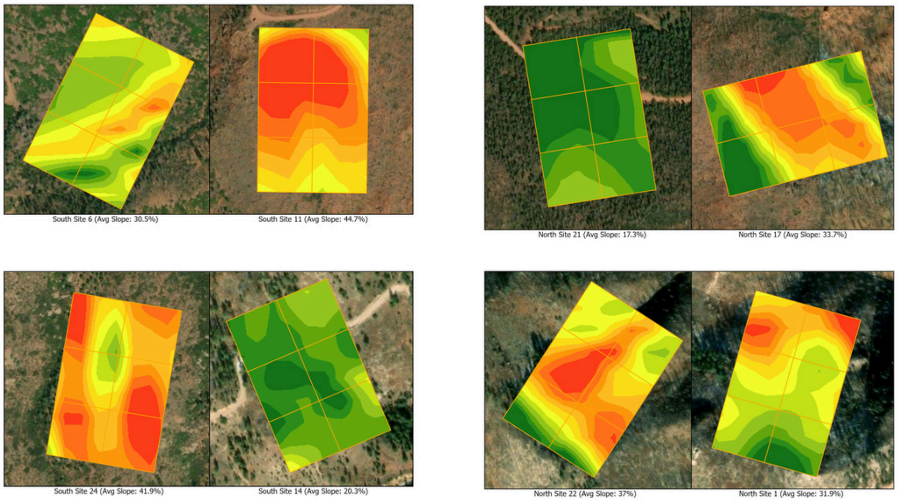


Figure 10. Calculated percent slope percent for each site.

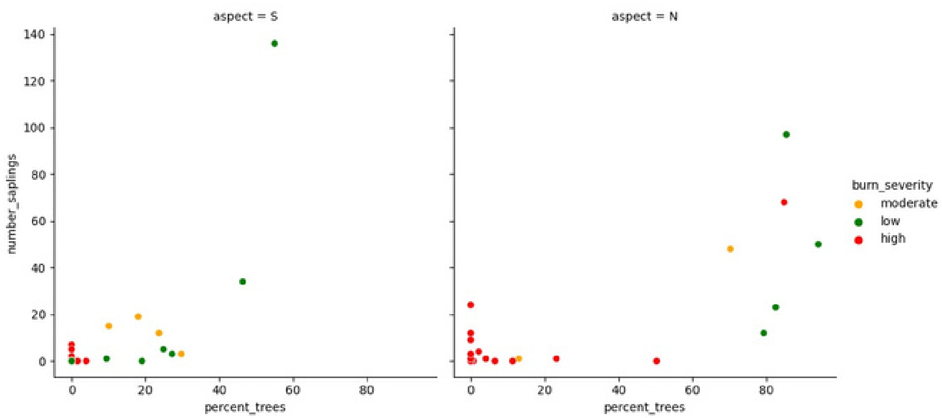


Figure 10. Frequency and occurrence of seedlings and saplings in relation to GIS classified north- and south-facing slopes.

```
. logistic sap_pres percent_trees percent_shrubs percent_grass burnSeverityNumber mean_slope elevation

Logistic regression                                     Number of obs =     42
                                                        LR chi2(6)    =  39.53
                                                        Prob > chi2   = 0.0000
Log likelihood = -7.6067099                             Pseudo R2     = 0.7221
```

sap_pres	Odds ratio	Std. err.	z	P>|z|	[95% conf. interval]	
percent_trees	1.224089	.1705572	1.45	0.147	.9315616	1.608475
percent_shrubs	.9460832	.0406859	-1.29	0.197	.8696084	1.029283
percent_grass	1.044927	.04318	1.06	0.288	.9636326	1.13308
burnSeverityNumber	3.415343	3.818008	1.10	0.272	.3818363	30.54861
mean_slope	.2815047	.1725239	-2.07	0.039	.0846867	.9357415
elevation	1.037243	.0177545	2.14	0.033	1.003022	1.072631
_cons	2.56e-33	9.33e-32	-2.06	0.040	2.22e-64	.0294214

```
Note: _cons estimates baseline odds.
Note: 0 failures and 7 successes completely determined.
```

Table 2. Results of logistic linear regression model using all site characteristics.

severity of each quad is a predictor of seedling and sapling presence. Burn severity was not significant (Table 2).

Our analysis suggests there is some linear relationship between the number of saplings and percent cover of grass (p-value 0.002), shrubs (p-value 0.004), and trees (p-value 0.007). As the percent cover of grass increases by 1%, we see a 4.06% decrease in the number of saplings per quad (CI =95%). As the percent cover of shrubs increases by 1%, we see a decrease of 3.41% in the number of saplings per quad (CI =95%). As the percent cover of trees increases by 1%, we see an increase of 3.85% in the number of saplings per quad (CI =95%). No other explanatory variables were significant (Table 3).

Preliminary results of our collected day are limited by the average of seedlings and saplings in 48 quadrants in seven sites in burn day one of the 2012 Waldo Canyon fire. We aim to expand our dataset in Phase II (burn day two) and Phase II (burn day three) of this long-term study.

Site	Land Class	AVG Percent Change
N1	Tree	-12.17
N17	Tree	-100.00
N21	Tree	-94.00
N22	Tree	-77.00
Total Percent Change in Tree cover in North-facing sites		**-70.79**
Site		
S6	Tree	-100.00
S11	Tree	-94.00
S14	Tree	-15.00
Total Percent Change in Tree cover South-facing sites		**-69.67**
Site	**Land Class**	**AVG Percent Change**
N1	Shrub	547.00
N17	Shrub	-100.00
N21	Shrub	-59.00
N22	Shrub	365.00
Total Percent Change in Shrub cover North-facing sites		**188.25**
Site		
S6	Shrub	-60.00
S11	Shrub	125.00
S14	Shrub	-100.00
Total Percent Change in Shrub cover South-facing sites		**-11.67**
Site	**Land Class**	**AVG Percent Change**
N1	Grass	7.39
N17	Grass	9.27
N21	Grass	727.00
N22	Grass	-32.00
Total Percent Change in Grass cover North-facing sites		**177.92**
Site		
S6	Grass	-5.00
S11	Grass	-46.00
S14	Grass	-10.00
Total Percent Change in Grass cover South-facing sites		**-20.33**

Table 3. Comparison of average percentage differences in land cover classifications in sites on northern aspects and southern aspects. We calculated the total average of percent difference in each vegetation class before (2011) and after (2023) the 2012 Waldo Canyon fire in north-facing sites compared to sites in south-facing sites in the burn day one area. South-facing sites support 2.265 times less shrubs or 226.5% more shrubs are established on north-facing sites following fire than on south-sloping sites. The average percent cover of grass on southern exposures is 2 times less than sites with northern exposure; 200% more grass has established on north-facing slopes than on south-facing slopes.

Preliminary Results:

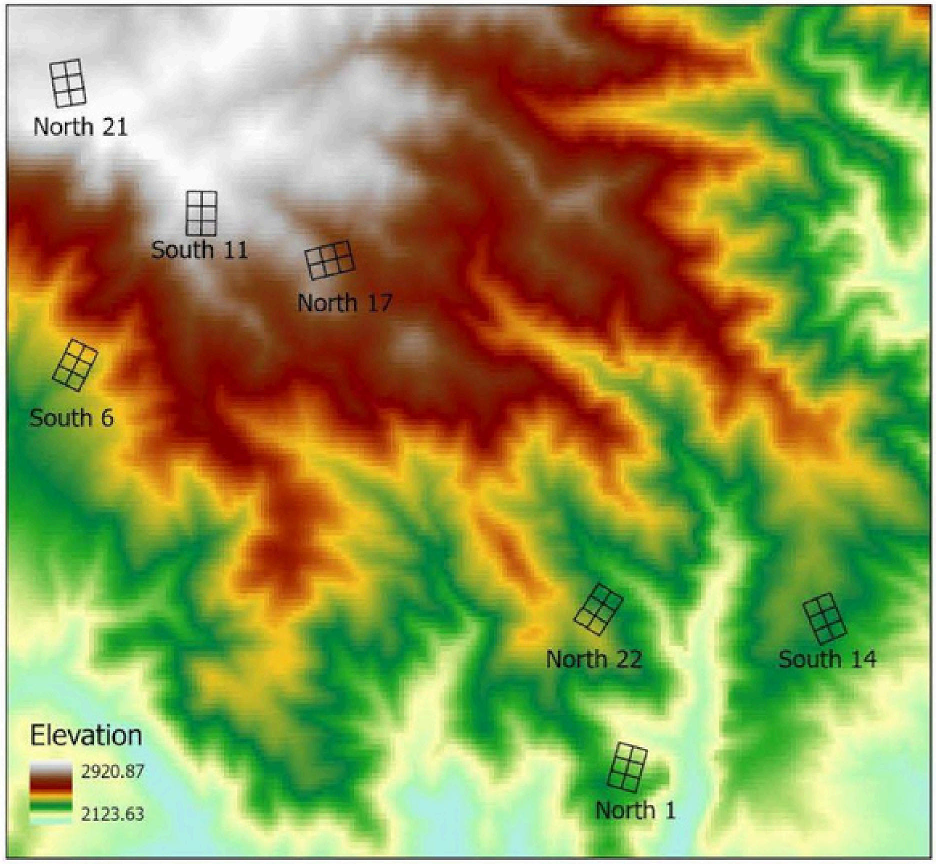
For our preliminary findings, a logistic regression analysis of the data suggests that mean elevation (p-value 0.033) and mean slope (p-value 0.039) influence the presence of seedlings and saplings. The odds of seeing seedlings increases 1.325 with a one unit (%) increase in mean slope per quad, contrary to what we would have hypothesized (Table 4). Quads ranged from a mean slope of 6.25% to 27.96% (Figure 10). This suggests the stress-tolerance of ponderosa pines and their ability to grow in difficult terrain. The odds of seedlings and saplings being present increases 2.82 times with a one unit increase in mean elevation (meters) per quad. The mean elevation per quad ranged from 2359 meters to 2872 meters. This data aligns with the elevational gradient in which ponderosapine are typically found (Figure 11).

A GLM log linear regression analysis of the data suggests some linear relationship after the log transformation of the y variable (number of saplings per quad). This analysis suggests there is some linear relationship between the number of saplings and percent cover of grass (p-value 0.002), shrubs (p-value 0.004), and trees (p-value 0.007; Table 4).

Findings:

We wanted to know whether *Pinus ponderosa* regeneration is occurring in the 12-year-old day one burn area and, if so, what influences the likelihood of seeing seedlings and saplings across a range of physical site conditions in Waldo Canyon. We were also interested in whether burn severity of each quad is a predictor of seedling and sapling presence. Additionally, we explored whether there is a linear relationsup among the number of saplings found per quad and the physical site conditions we measured.

A logistic regression analysis of the data suggests that mean elevation (p-value 0.033) and mean slope (p-value 0.039) influence the presence of seedlings and saplings.




```
. glm log_saplings percent_trees percent_shrubs percent_grass burnSeverityNumber mean_slope elevation north

Iteration 0:  Log likelihood = -31.454611

Generalized linear models                         Number of obs     =         27
Optimization     : ML                             Residual df       =         19
                                                  Scale parameter   =   .8551247
Deviance         =  16.24736928                   (1/df) Deviance   =   .8551247
Pearson          =  16.24736928                   (1/df) Pearson    =   .8551247

Variance function: V(u) = 1                       [Gaussian]
Link function    : g(u) = u                       [Identity]

                                                  AIC               =   2.922564
Log likelihood   = -31.45461127                   BIC               =  -46.37353
```

log_saplings	Coefficient	OIM std. err.	z	P>|z|	[95% conf.	interval]
percent_trees	.0385625	.0144111	2.68	0.007	.0103173	.0668077
percent_shrubs	-.034106	.0117657	-2.90	0.004	-.0571663	-.0110457
percent_grass	-.0406314	.0128435	-3.16	0.002	-.0658042	-.0154586
burnSeverityNumber	.3716951	.2883196	1.29	0.197	-.193401	.9367911
mean_slope	-.0347179	.0540114	-0.64	0.520	-.1405783	.0711425
elevation	-.0026926	.0018651	-1.44	0.149	-.0063481	.0009629
north	-.0440691	.4775337	-0.09	0.926	-.9800179	.8918798
_cons	8.257201	3.973912	2.08	0.038	.4684762	16.04592

Table 4. Results of GLM linear regression model using all site characteristics.

A GLM log linear regression analysis of the data suggests some linear relationship after the log transformation of the y variable (number of saplings per quad). This analysis suggests there is some linear relationship between the number of saplings and percent cover of grass (p-value 0.002), shrubs (p-value 0.004), and trees (p-value 0.007; Table 4).

Discussion:

Since our lower elevation study sites were in pinyon- juniper woodlands, it makes sense that we would find more ponderosa

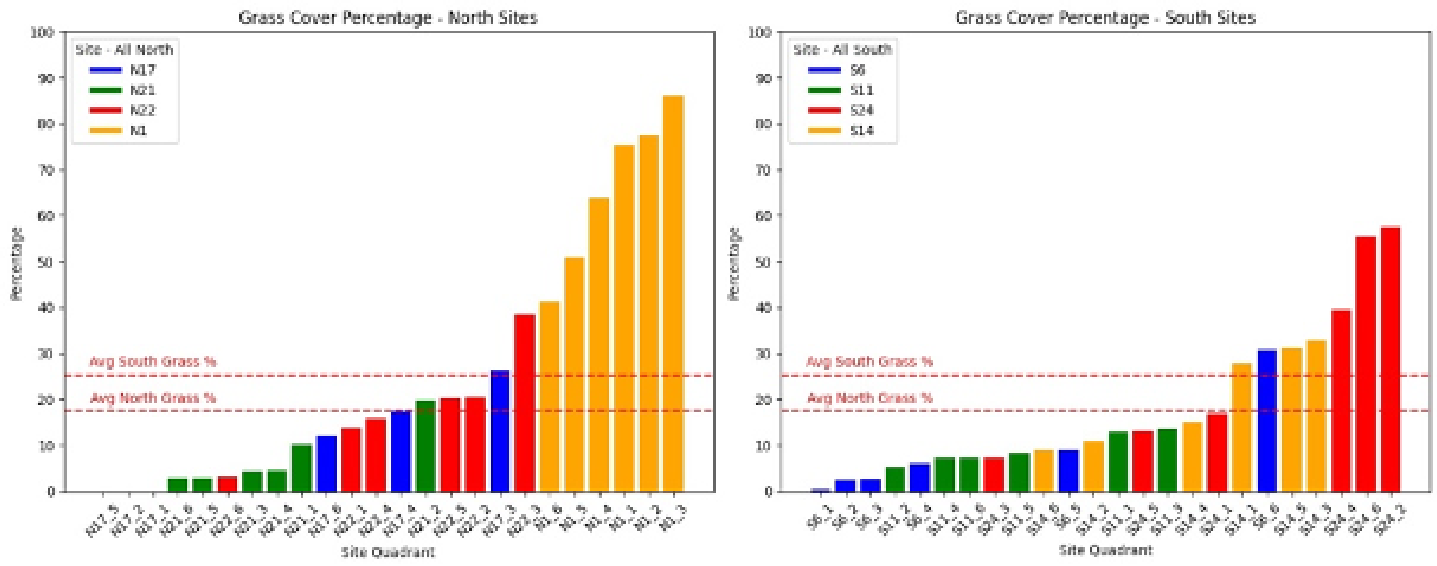


Figure 12. Frequency and occurrence of seedlings and saplings in relation to GIS generated percent grass cover.

pine seedlings at higher elevations. In addition, there was no significant relationship between the likelihood of seeing a seedling and burn severity. Due to our small sample size, it is possible that a larger dataset could reveal trends between burn severity and ponderosa pine seedling likelihood.

As the percent cover of grass increases by 1%, we saw a 4.06% decrease in the number of saplings per quad. Similarly, as the percent cover of shrubs increases by 1%, we calculated a decrease of 3.41% in the number of saplings per quad.

These findings suggest that grasses and shrubs, often primary successors after a fire, outcompete ponderosa pine seedlings. The mechanisms of competition may potentially include blocking sunlight and taking water away from seedlings. On the other hand, as the percent cover of trees increased by 1%, the number of saplings per quad increased 3.85%. Typically, live trees were found in low severity burn sites. In low-moderate burn severity sites, primary successors like grasses and shrubs were unable to take over (Figure 12). Saplings were more likely to be observed in sites where there is less competition with grasses and shrubs. Furthermore, ponderosa pine saplings are more likely to regenerate when there is a live tree nearby due to their short-lived seed bank. In areas where trees survived the burn and are still able to reproduce, ponderosa pine seeds are potentially more abundant.

<u>Conclusion:</u>

The 2012 Waldo Canyon fire devastated acres of ponderosa pine dominated forests and incinerated homes and buildings as it swept upslope.Our study aims to determine if dominant historic ponderosa pine forests are regenerating post-fire under dramatically different climate conditions. We aim to identify if and where in the landscape the species is and will likely survive. This information will help guide federal and state agencies in designing restoration and land management practices as well as deepen our understanding of the resultant impacts of a changing climate.

<u>On-going Research:</u>

We embarked on a phase two of the project this summer in effort to build our field dataset and map the landscape-scale changes observed using GIS techniques. This preliminary work, several has generated additional questions.

What can we say about the complexity (heterogeneity) of the sites in 2011 and in 2023?

Is the landscape patchwork more complex following fire?

At what scale do we observe the greatest and least amount of heterogeneity?

How does landscape heterogeneity influence habitat diversity, species richness, and the movement of wildlife?

What soil conditions (e.g., mycorrhizae; chemical properties) exist in sites where saplings are observed more frequently compared to sites where only ponderosa pine dead trees stand? ▲