ASSESSMENT OF THE INITIAL PINE GROVE FIRE RECOVERY

by

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of the requirements for the degree

of

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DEDICATION

To my understanding, and patient wife who supported me through this program and listened to me work through materials and topics when I became overwhelmed. Being the rock that I could lean on in times where I needed that support the most.

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I thank all the LRES and MSSE professors I interacted with during my time at Montana State University. The program offered me an opportunity to pursue a Master's degree with the limited time I had available.

TABLE OF CONTENTS

1. INTRODUCTION 1

Research Objectives 3
Rationale of the Study 3
Literature Review 5
Remote Sensing for Post-Fire Analysis 6
Fire Severity and Topographic Influences 6
Climate, Moisture, and Recovery Dynamics 7
Mining Impacts and Vegetation Stress 7

2. MATERIALS AND METHODS 8

Study Area 8
Satellite Imagery 10
Burn Perimeter 10
Topography 11
Climate Data 11
Mining and Proximity Data 11
Remote Sensing Indices and Calculations 12
Normalized Difference of Vegetation Index (NDVI) 12
Normalized Difference Moisture Index (NDMI) 13
Diferrence of Normalized Burn Ratio (dNBR) 13
Principal Component Analysis 14
Analytical Framework 15
Ethical Considerations 16

3. RESULTS 17

NDVI Time-Series Analysis 17
Pre-Fire Baseline (2020) 17
Immediate Post-Fire Conditions (2021) 17
Early Recovery (2022) 18
Continued Recovery (2023) 19
NDMI Time-Series Analysis 20
Moisture Conditions and Recovery Correlations 20
Topographic and Spatial Patterns 22
Principal Component Analysis Results 26
Zonal Comparison Summary 28

TABLE OF CONTENTS CONT.

Summary of Findings 30

4. DISCUSSION 31

Vegetation Recovery Patterns and Dynamics 31
Moisture Availability and Climatic Influences 32
Topographic and Terrain Effects 32
Influence of Legacy Mining Activities 33
Integration of Remote Sensing and PCA Approaches 34
Comparative Evaluation with Previous Studies 34
Management Implications and Recommendations 35
Study Limitations 36

REFERENCES CITED 37

LIST OF FIGURES

Figure Page

1. Figure 1: Map of Montana with arrow pointing to southern end of Fort Belknap Indian Reservation. 1
2. Figure 2: 17
3. Figure 3: 18
4. Figure 4: 22
5. Figure 5: 8
6. Figure 6: 17
7. Figure 7: 18
8. Figure 8: 22
9. Figure 9: 8
10. Figure 10: 17
11. Figure 11: 18
12. Figure 12: 22

ABSTRACT

The Pine Grove Fire of August 2021 burned approximately 65.39 km^2 on the southern end of the Fort Belknap Indian Reservation in the Little Rocky Mountains in north-central Montana, an area already affected by legacy disturbances from the Zortman–Landusky gold mines. My study evaluates vegetation recovery from 2021–2023, using imagery from 2020 as a pre-burn baseline, covering a period from 2020-2023.The purpose of my study is to use Landsat-8 imagery processed in Google Earth Engine, I derived annual August composites of the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI) for the full burn perimeter and three proximity zones: mine-adjacent (Zone 1), transitional (Zone 2), and Pine Grove (Zone 3). Digital elevation models, climate data, and Principal Component Analysis (PCA) were used to relate recovery patterns to topography, moisture, and substrate conditions. Pre-fire NDVI indicated moderately dense vegetation (mean ≈ 0.70). Immediately after the fire, the mean NDVI decreased by about 0.37, with the lowest values in the central and southern sectors. By 2023, NDVI recovered to ≈0.53, and NDMI also increased, indicating substantial but incomplete regrowth under semi-arid conditions and recent drought. Zone-level summaries show that Zone 1 generally maintained the lowest NDVI and NDMI, whereas Zone 3 exhibited the highest values; however, one-way ANOVAs detected no statistically significant differences in mean August NDVI or NDMI among zones over the four years. Recovery was instead strongly structured by topography and moisture: north- and east-facing, low-slope, and drainage positions showed faster regrowth than steep, south-facing slopes. PCA, which explained 99.38% of spectral variance in the first three components, highlighted persistent barren or sparsely vegetated patches near the mine complex and more extensive rangeland and shrub recovery in central and northern portions of the burn. Overall, the results suggest that while legacy mining influences recovery at patch scales, broad late-summer greenness and moisture have largely converged across the burn perimeter. The integrative NDVI–NDMI–PCA framework provides a reproducible approach for long-term post-fire monitoring and can inform restoration planning and tribal land-management decisions on Fort Belknap and in similar semi-arid, disturbance-affected landscapes.

INTRODUCTION

The Pine Grove Fire began on August 16, 2021, and burned about 65.39 km^2 in the Little Rocky Mountains. Located at the southern end of the Fort Belknap Indian Reservation in north-central Montana (Figure 1) (Bureau of Land Management [BLM], 2021), the area has a long history of mining disturbances (Exploration and Development, n.d.). Gold mining operations started in the late 1800s, eventually leading to the establishment of the open-pit cyanide heap leach mine run by Pegasus Gold Corporation. Pegasus ceased operations in 1997 due to falling gold prices and subsequently declared bankruptcy. As a result, contaminated sites and cleanup costs were left to the State of Montana and taxpayers (Ej atlas, n.d.).

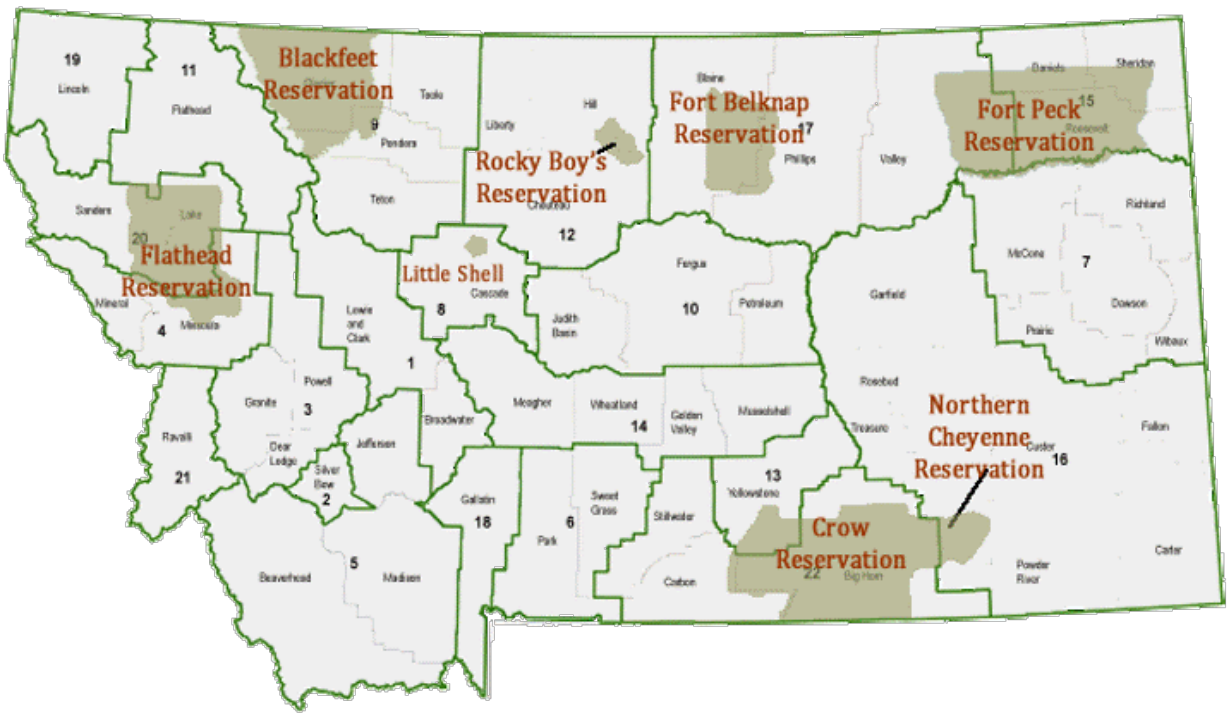


Figure 1. Map of Montana with arrow pointing to southern end of Fort Belknap Indian Reservation. (Indian Law Portal, 2025).

Does the proximity to the former mining sites influence vegetation recovery rates and patterns following the Pine Grove Fire?

This question stems from the hypothesis that areas near the Zortman-Landusky mines may experience slower plant recovery, possibly due to residual pollution, altered soils, or water issues resulting from the mines. Areas farther from the mines may recover more quickly, even if they are close to other sites, such as the Pine Grove community. This information will help show how old mines affect fire recovery in dry mountain areas.

The mining operation included two treatment plants: one in Swift Gulch on the reservation side and another to the south. These plants were built to treat mine runoff and reduce the effects of acid mine drainage. Although reclamation has been attempted, long-term effects on hydrology, soil chemistry, and vegetation recovery remain unclear. The aftermath of the Pine Grove Fire provided an opportunity to assess ecological recovery in an area region that has already been influenced by legacy mining disturbances, to better inform land management of conditions in areas that hold cultural and spiritual significance to the tribes living on the Fort Belknap Indian Reservation when assessing impacted areas for recovery efforts.

Therefore, the goal of my study is to assess the vegetation recovery in the Pine Grove Fire burn area using remote sensing technologies and time-series analysis of Landsat-8 imagery. The focus of the research will be on comparing the recovery patterns of areas near the Zortman-Landusky Mines with those closer to the Pine Grove community and intermediate zones.

Research Objectives

My study objectives are:

1. Assess post-fire vegetation recovery across the Pine Grove Fire Burn perimeter using multi-year Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI) time series derived from Landsat-8 imagery.
2. Examine how topography, climate, and soil moisture are related to spatial variability in vegetation recovery.
3. Compare recovery dynamics between mining-impacted and non-impacted areas.
4. Evaluate the potential for remote sensing technologies to serve as tools for long-term ecological monitoring and restoration planning on the Fort Belknap Indian Reservation.

Rationale of the Study

Understanding post-fire vegetation recovery is crucial for managing areas affected by both anthropogenic and natural disturbances. Fires in semi-arid environments, such as the Little Rocky Mountains, often trigger complex regeneration patterns influenced by factors including soil moisture, slopes, and land-use history. Using remote sensing, climate, and topographical data, my study aims to raise awareness about how the legacy impacts of mining are related to natural recovery processes. My research contributes to the ongoing efforts to improve ecosystem restoration efforts on indigenous lands, where the stewardship of land, cultural resilience, and sovereignty intersect with environmental degradation. Evaluating the recovery of the affected area using NDMI and NDVI indices enables a replicable, quantitative assessment of recovery that informs tribal, state, and federal agencies responsible for land and resource management. The research in my study recognizes the cultural importance of the Little Rocky Mountains to

the Fort Belknap Indian Community. Engagement with tribal members and tribal entities is a crucial component of this work.

Scope

The study area covers the whole Pine Grove Fire zone, as mapped by the Monitoring Trends in Burn Severity (MTBS) database (2021). The analysis will span four years, from August 2020 (before the fire) through August 2023, covering the period before, during, and after the fire. Main data and steps used are:

- Imagery: Landsat-8 data acquired via the U.S. Geological Survey (USGS) GloVis platform.
- Fire Perimeter: MTBS shapefiles for delineating the Pine Grove Fire boundary.
- Climate Data: Local data from Hays, Montana (BestPlaces, n.d.) and PRISM Climate group normal (PRISM Climate Group, n.d.).
- Topography: Digital Elevation Models (DEMS) to analyze slope, aspect, and elevation (USGS, n.d.-a).
- Indices:
    - NDVI = (NIR – Red)/(NIR + Red) (USGS, n.d.a; ICT International, 2024).
    - NDMI = (NIR – SWIR1)/(NIR + SWIR1) (USGS, n.d.-c).
- Analysis Tools: Google Earth Engine (GEE) for automated time-series analysis; Principal Component Analysis (PCA) for pattern recognition and dimensionality reduction (Ghouzlane & Fistikoglu, 2024). One-way ANOVA to evaluate differences in the NDVI and NDMI across zones.

By comparing NDMI and NDVI over time and in locations near the old Zortman-Landusky Mines and other human-made sites, my study will observe plant health and moisture levels recover after the fire.

Literature Review

Post-Fire Vegetation Recovery and Remote Sensing Applications

Fire is a natural part of many ecosystems; however, vegetation recovery varies widely across different climates, landscapes, and disturbance histories. Advances in remote sensing enable the assessment of post-fire vegetation dynamics over time and across broad spatial scales. Vegetation indices, such as the NDVI and NDMI, are especially useful because of their correlation with photosynthetic activity and moisture content, respectively (Pérez-Cabello et al., 2021; Liu et al., 2023). NDVI, derived from the ratio of near infrared (NIR) to red reflectance, provides a proxy for plant health and vigor. NDVI has been extensively used in burn recovery studies for its cost-effectiveness and strong correlation with biomass regeneration (Ghouzlane & Fistkoglu, 2024; Tonbul et al., 2016). NDMI, however, based on NIR and short-wave infrared (SWIR) reflectance, offers insight into the moisture conditions of vegetation and soil (USGS, n.d.-c). In combination, NDMI and NDVI form a complementary toolkit for assessing ecosystem recovery trends following fire disturbances.

Remote Sensing for Post-Fire Analysis

Several studies have demonstrated the utility of multi-temporal satellite imagery in post-fire monitoring. Sagynbavera et al. (2023) applied NDVI and GIS technologies to evaluate pine forest regeneration in Kazakhstan, finding that remote sensing allows for effective long-term monitoring of restoration processes. Liu et al. (2023) similarly assessed fire extent and post-fire recovery across semi-arid climate gradients, confirming NDVI's performance over other indices under dry conditions.

Principal Component Analysis (PCA) has been incorporated to enhance classification accuracy in complex landscapes by reorienting spectral data along new axes, improving discrimination between burned and unburned areas (Ghouzlane & Fistikoglu, 2024). Combining multi-temporal PCA with NDVI improves mapping accuracy by emphasizing temporal variances associated with regrowth.

Fire Severity and Topographic Influences

Topography plays a substantial role in post-fire regeneration. Tonbul et al. (2016) analyzed fire severity and regeneration in Mersin, Turkey, using multitemporal imagery, finding that slope and aspect strongly influenced burn severity. North-facing slopes and valley bottoms typically exhibit higher moisture retention and cooler microclimates, promoting faster regrowth in comparison to south-facing slopes. DEMs are critical in quantifying these effects and are widely used to relate post-fire vegetation metrics to terrain attributes (USGS, n.d.-a).

Climate, Moisture, and Recovery Dynamics

Climate conditions, including temperature, precipitation, and humidity, directly impact recovery rates following fire events. Data from the Hays, Montana area indicate a continental climate with hot summers and cold, snowy winters, characterized by an average annual precipitation of 40.64-60.96 cm (BestPlaces, n.d.; PRISM Climate Group, n.d.). The semi-arid conditions, coupled with multi-year drought events, can alter successional patterns and slow recovery. NDMI time-series analyses are useful in correlating moisture trends with recovery potential, especially in moisture-limited ecosystems.

Mining Impacts and Vegetation Stress

Areas near former mining operations often show degraded soil and water quality, which can inhibit plant regeneration. Heavy metals and acid mine drainage (AMD) can alter soil pH, limit nutrient availability, and reduce vegetation cover, hindering natural recovery processes. Although previous studies have largely focused solely on the effects of fire, the interaction between legacy mining impacts and post-fire recovery remains understudied. This research aims to close that research gap by comparing mine-adjacent versus non-mined portions of the Pine Grove Fire area.

Current literature supports the effectiveness of remote sensing indices, such as NDMI, NDVI, and PCA, in monitoring fire recovery (Perez-Cabello et al., 2021; Liu et al., 2023; Ghouzlane & Fistikoglu, 2024; Sagynbavera et al., 2023). Few studies, however, examined the effects of legacy mining disturbances on post-fire ecological recovery using these tools. The Pine Grove fire area, characterized by overlapping areas of disturbance by fire and mining, offers a unique opportunity to evaluate these interactions. My study will expand upon previous research

by employing multi-index time-series analyses to evaluate recovery differentials across environmentally distinct subregions of the Little Rocky Mountains.

MATERIALS AND METHODS

Study Area

The study area (Figure 2) encompasses the Little Rocky Mountains on the southern end of the Fort Belknap Indian Reservation in north-central Montana, which was affected by the Pine Grove Fire. The area is primarily composed of ponderosa pine (*Pinus ponderosa*), Douglas-Fir (*Pseudotsuga menziesii*), and mixed grassland species typical of semi-arid mountain environments. The area is both ecologically and culturally important to the Aaniih (Gros Ventre) and Nakoda (Assiniboine) nations, who maintain stewardship over the land. The Pine Grove Fire, which started August 16, 2021, burned approximately 65.39 km^2 of mixed forest and rangeland vegetation across the southern slopes of the Little Rocky Mountains (BLM, 2021; InciWeb, 2021).

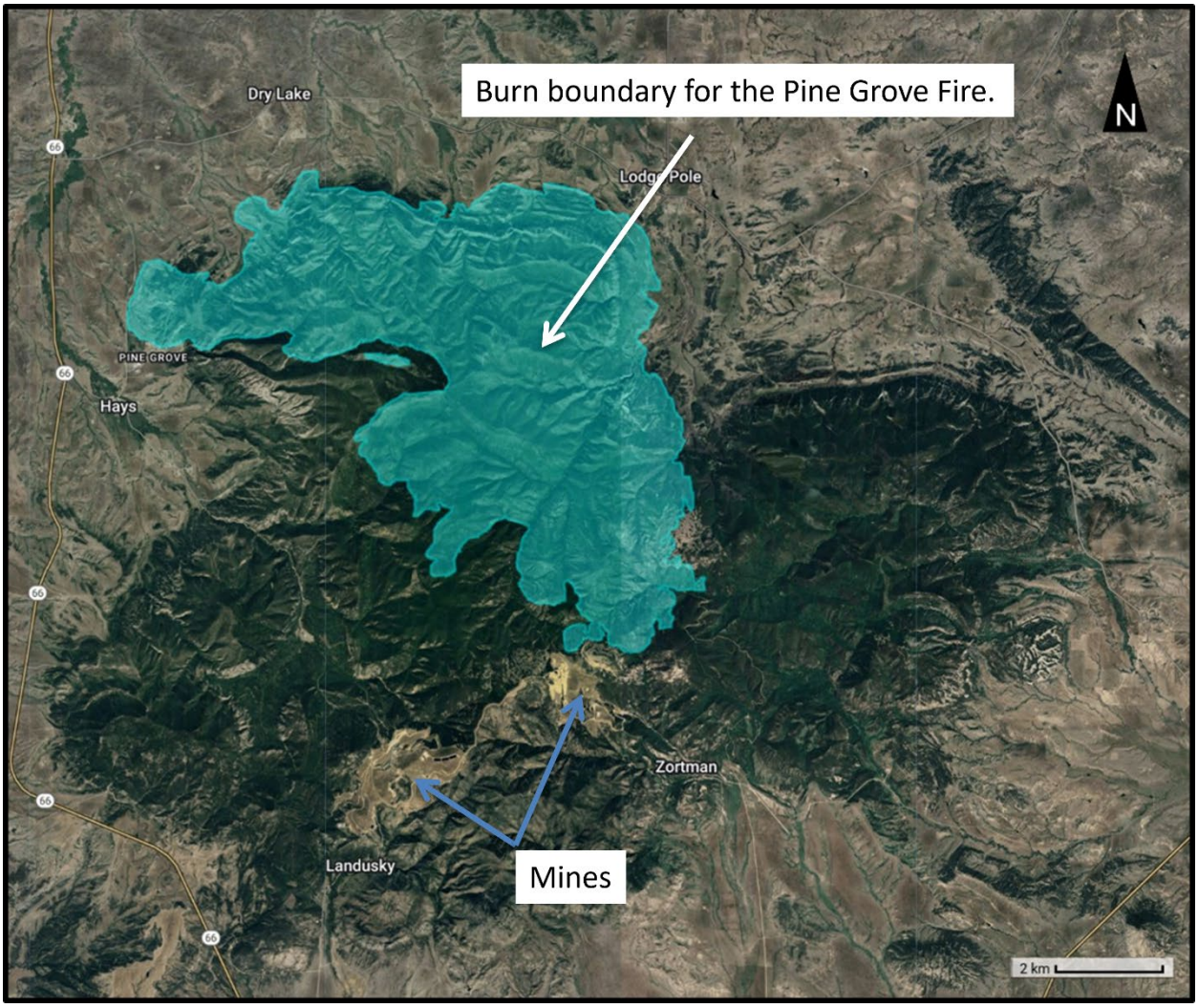


Figure 2: Pine Grove Fire Study area map.

The region's environmental history is shaped by the legacy of mining activities at the Zortman-Landusky Mines, situated near the southern boundary of the reservation. Gold mining in the area began in the late 1800s and continued until just before the start of the 21st century, when Pegasus Gold Corporation ceased operation and declared bankruptcy. The resulting AMD and heavy metal contamination continue to pose environmental challenges, with two treatment

plants operating to mitigate the contaminated water flows, one at Swift Gulch and another to the south on non-reservation lands.

The climate of the Little Rocky Mountain region is classified as continental, with warm summers and cold, snowy winters. Data from Hays, Montana, located southwest of Pine Grove, indicate that summer temperatures average approximately 21.11℃, with highs in August averaging 27.17℃ (BestPlaces, n.d.). The area experiences approximately 4.9 days each August with temperatures exceeding 32.22℃, while the average humidity during the same period is 44.2% (BestPlaces, n.d.). Average precipitation in August is 3.04 cm, occurring over approximately 6 days (BestPlaces, n.d.). Annual precipitation in the region ranges from 40.64-60.96 cm, according to the PRISM Climate Group (n.d.). The semi-arid to sub-humid conditions contribute to the low moisture availability during the growing season, an important consideration when assessing post-fire recovery. Multi-year droughts in the region may further delay the recovery of vegetation, especially in areas where soil chemistry is degraded due to the legacy effects of mining.

Satellite Imagery

Primary imagery was obtained from the USGS GloVIS platform. Landsat-8 Operational Land Imager (OLI) data were selected due to their 30-meter spatial resolution and high temporal consistency. The analysis covers the period August 2020 to August 2023, encompassing pre-fire, burn year, and post-fire recovery intervals.

Burn Perimeter

The burn perimeter shapefile for the Pine Grove Fire was acquired from the Monitoring Trends in Burn Severity (MTBS) database (2021). The shapefile delineates the official fire

boundary and includes per-pixel burn severity data derived from Normalized Burn Ratio (NBR) calculations. These data allow the stratification of the study area into zones of low, moderate, and high burn severity.

Topography

A DEM was used to extract slope, aspect, and elevation information, enabling the evaluation of the terrain's influence on vegetation recovery. DEMs represent bare-earth elevation and are foundational for hydrological and topographic modeling (USGS, n.d.-a). Slope and aspect were derived using GEE terrain functions to correlate vegetation indices with elevation gradients and solar exposure.

Climate Data

Climate normals were obtained from the PRISM Climate Group (n.d.), while monthly and annual climate data were sourced from BestPlaces (Hays, Montana).

Mining and Proximity Data

To evaluate the influence of legacy mining disturbances, spatial data representing the extent of the Zortman-Landusky Mine complex were included. These data were obtained from MT DEQ and overlaid on the burn perimeter shapefile and then divided into three separate zones (Figure 3).

1. Zone 1: Near Mine Sites- Areas within 2 kilometers of mine boundaries.
2. Zone 2: Transitional Zone- Areas between 2 and 5 kilometers from the mines.
3. Zone 3: Pine Grove Zone- Areas located more than 5 kilometers from mine boundaries, nearer the Pine Grove Community.

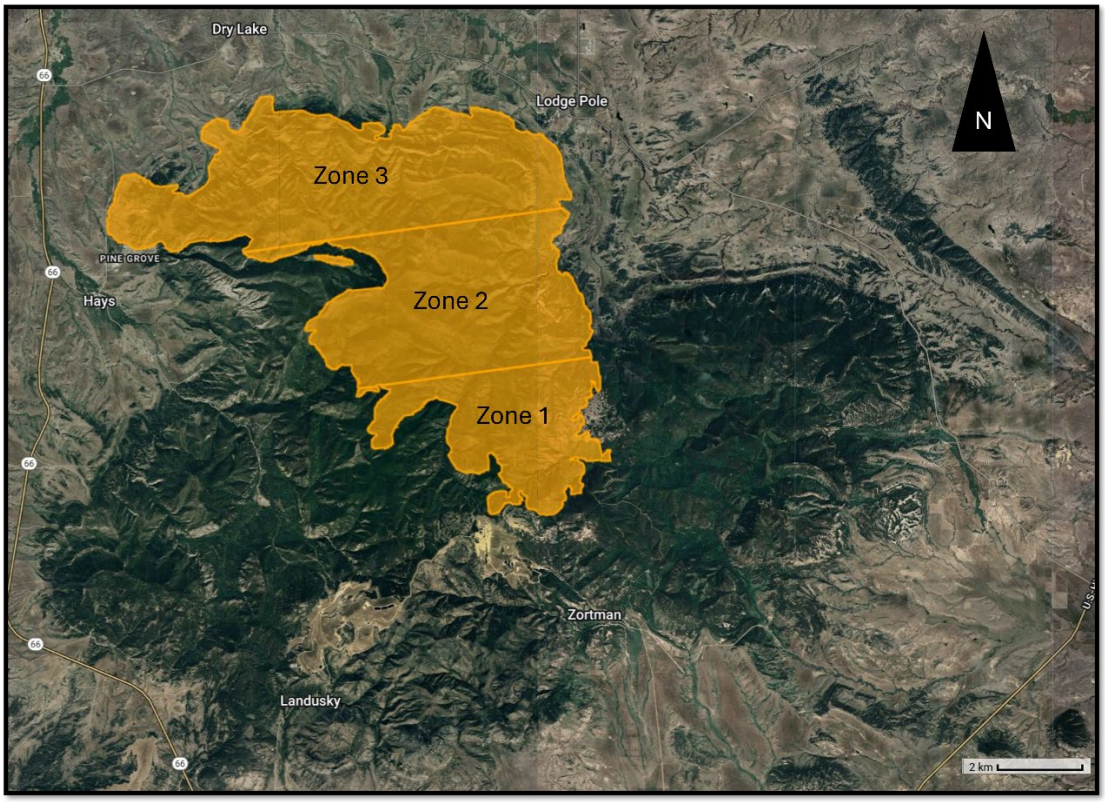


Figure 3. Map of Zones within Pinegrove Fire burn perimeter.

This zonal division enabled a comparative analysis of recovery trends among areas potentially affected by mine-related soil or water contamination, compared to those from less-impacted areas.

Remote Sensing Indices and Calculations

Normalized Difference Vegetation Index (NDVI)

NDVI was used as a proxy measure of vegetation greenness and overall health. NDVI values range from -1.0 to +1.0, with higher values representing denser and healthier vegetation (USGS, n.d.-b; ICT International, 2024). The NDVI was calculated using Landsat-8 Bands 5(NIR) and 4(Red) according to the equation:

NDVI = (NIR – Red)/(NIR + Red) (USGS, n.d.a; ICT International, 2024).

NDVI values were extracted for each of the three spatial zones and averaged by time interval pre-fire, post-fire, one-year post-fire, and two years post-fire.

Normalized Difference Moisture Index (NDMI)

NDMI was used as a proxy for vegetation and soil moisture, critical to understanding recovery dynamics under semi-arid conditions (USGS, n.d.-c). It was calculated using Landsat-8 bands 5 (NIR) and 6 (SWIR1) according to the formula:

NDMI = (NIR – SWIR1)/(NIR + SWIR1) (USGS, n.d.-c).

NDMI time-series analyses were conducted in parallel with NDVI to examine how moisture variability was related to vegetation recovery across spatial zones.

Difference Normalized Burn Ratio (dNBR)

dNBR was used to quantify burn severity for the Pine Grove Fire. NBR was first calculated for August 2020, and then for August 2021 (pre and post-fire respectively) using near-infrared, and short-wave infrared (SWIR2) bands. For each date, NBR was calculated using the equation:

NBR= (NIR – SWIR2)/(NIR + SWIR2) (USGS, n.d.)

The dNBR surface was then obtained by subtracting pre-fire NBR from post-fire NBR, dNBR = (post-fire NBR (NBR = (NIR – SWIR2)/ (NIR + SWIR2)) – (pre-fire NBR (NBR = (NIR – SWIR2)/ (NIR + SWIR2)). The higher values for dNBR indicate greater reduction in live vegetation, showing higher burn severity, where values near zero or negative indicate unburned or recovering vegetation (un-spider knowledge portal, n.d.). The dNBR raster (Figure) was then classified, using published threshold ranges (<0.10, 0.10— <0.27, 0.27— <0.44, and >0.44

dNBR), into standard severity classes (unburned, low, moderate, and high) (un-spider knowledge portal, n.d.).

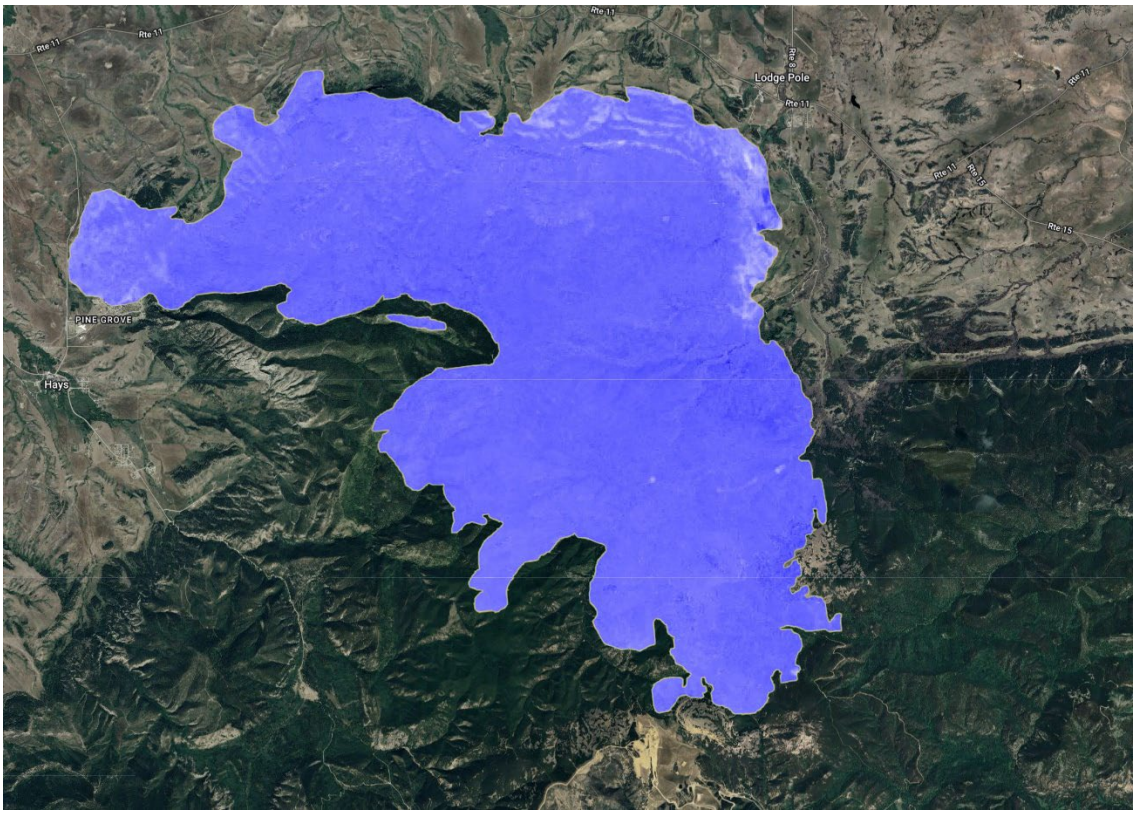


Figure 4. dNBR of study area utilizing composite images of August 2020 and August 2021.

Principal Component Analysis (PCA)

PCA was used to enhance and identify dominant spectral patterns associated with vegetation recovery (Ghouzlane & Fistikoglu, 2024). PCA reorients spectral data along orthogonal axes that represent maximum variance, thereby reducing redundancy in multispectral datasets.

For this analysis, land-cover classes were defined based on representative samples from pre-fire imagery (August 2020): Class 0- intact rangeland and forest, Class 1- mixed rangeland and intermediate or recovering shrub/grass, Class 2- persistently barren or mine-disturbed ground. Developed, barren, water, and burned areas were identified and used mask for non-vegetated features as opposed to being used as primary recovery classes. A multi-temporal stack of August images (2020–2023) was used as input to PCA to capture changes in spectral response through time.

Analytical Framework

Analyses were conducted within Google Earth Engine (GEE), enabling cloud-based computation and time-series visualization of Landsat-8 data. The analytical framework followed these steps:

1. Data Acquisition: Importing Landsat-8 imagery and fire perimeter shapefile, and DEM were imported into GEE.
2. Preprocessing: Masking of clouds and shadows using the QA_PIXEL band; converting digital numbers to top-of-atmosphere reflectance.
3. Zonal Statistics: The burn perimeter was divided into three proximity zones, with mean NDVI and NDMI values extracted from the burn perimeter and individual zones for each year. Class proportions were summarized from the PCA outputs. Mean dNBR values were summarized by zone to characterize the initial burn severity across the study area.
4. Spectral Index and PCA Calculations: For each yearly composite, the NDVI and NDMI were calculated. NBR was computed from the pre-fire (2020) and post-fire (2021) composites, and the dNBR was calculated from them to use as an initial index for burn

severity. A multi-year stack of the August composite images was then used as the input for the PCA. The first three components (PC1-3) were retained for subsequent classification and mapping.

5. Supervised Classification: Training samples were delineated in the pre-fire composite for the three vegetation classes used in the code: Class-0 (dense to moderately dense vegetation), Class-1 (intermediate to recovering shrub/grass and mixed rangeland), and Class-2 (persistently barren or mine-disturbed ground). Classes for developed and water features were selected to mask non-vegetated features as well. PC1-PC3 and selected spectral bands were used as predictor variables in a supervised classifier to map recovery classes across the burn area.
6. Temporal Analysis: NDVI and NDMI time series were generated at the study area and zone levels to evaluate vegetation and moisture recovery trends. These values were then used to compare the pre-fire and post-fire conditions. dNBR was used to provide a static baseline of initial fire impacts against which NDVI and NDMI were compared to.
7. Topographic Correlation: Overlaying slope and aspect layers derived from the DEM to qualitatively compare relationships between terrain, burn severity and recovery rates.
8. Statistical Evaluation: Conducting one-way ANOVA tests to evaluate differences in mean NDVI and NDMI among zones across time intervals.

Ethical Considerations

Artificial Intelligence tools, including large language models, were used in preparing portions of this manuscript under my supervision. These tools were applied for editing,

organization, and synthesis of literature; all interpretations, analyses, and conclusions remain my original work.

RESULTS

NDVI Time-Series Analysis

Pre-Fire Baseline (2020)

Pre-fire NDVI values (August 2020) established the baseline vegetation health prior to the Pine Grove Fire. NDVI values across the burn area ranged from 0.68 to 0.73, with an average for the entire zone of 0.70, indicating moderately dense vegetation. Spatial analysis revealed that Zone 1 (mine adjacent zones) exhibited the highest mean NDVI (0.73), reflecting healthy vegetation despite anthropogenic disturbance. Zone 3 (Pine Grove area) demonstrated the lowest NDVI (0.68), still within a range indicating moderately dense, and healthy vegetation. With Zone 2 close to Zone 1 NDVI mean values (0.72).

Immediate Post-Fire Conditions (2021)

Post-fire imagery from August 2021, captured shortly after containment, showed a substantial reduction in NDVI across all zones. The mean NDVI across the burn area dropped by 0.36, indicating widespread loss of vegetation cover and extensive soil exposure. Burn severity was greatest along broad northern and northeastern edges of the burn perimeter and in patches along the western edge near Pine Grove (Figure 5).

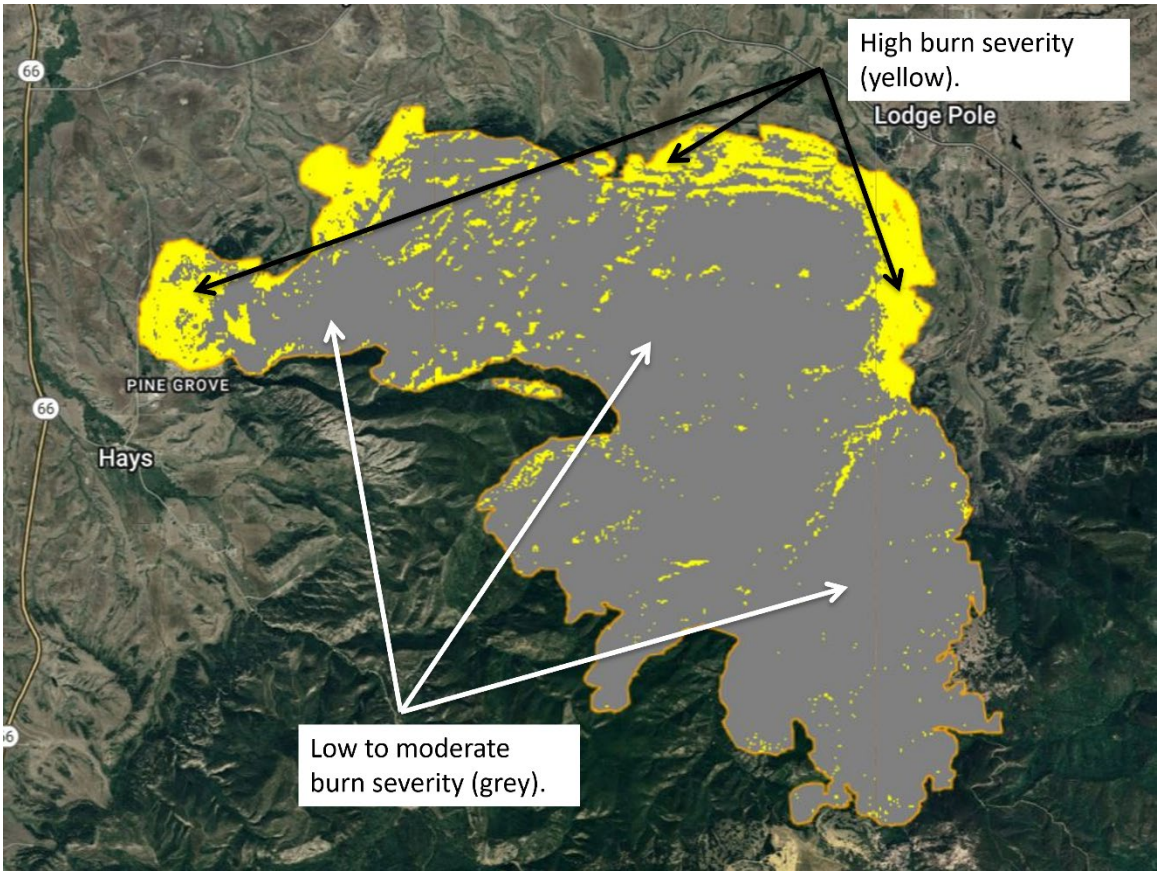


Figure 5: Burn severity output showing high severity burn (yellow) and low to moderate severity burn (gray).

Among proximity zones, Zone 2 had the lowest NDVI (mean=0.32), while Zone 3 retained slightly higher values (mean=0.34), reflecting partial survival of vegetation patches and less intense fire behavior near the periphery. Zone 1 NDVI was the highest value (mean=0.37) reflecting vegetation survival similar to but slightly higher than Zone 3.

Early Recovery (2022)

One year after the fire, NDVI analysis indicated visible signs of early successional vegetation regrowth across much of the burn area. The mean NDVI for the Pine Grove Fire burn perimeter rose to 0.48, representing a 29.7% increase from the immediate post-fire conditions.

Regrowth was most pronounced in the lower elevation valleys and north-facing slopes, where soil moisture and shade were higher.

Recovery rates varied among zones. Zone 2 displayed the highest NDVI (mean=0.50), while Zone 1 was the lowest (mean=0.44). The NDVI for Zone 3 was between these values (mean=0.44),

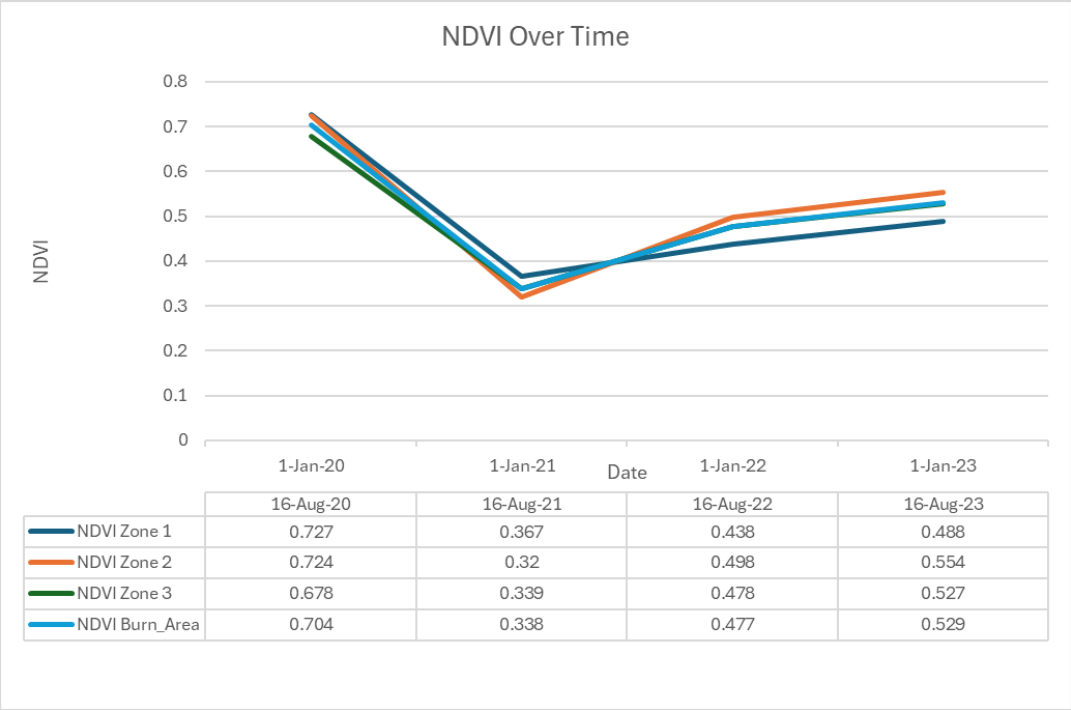
Continued Recovery (2023)

By August 2023, NDVI values across the burn area continued to increase, though spatial heterogeneity persisted; the overall burn perimeter NDVI rose to 0.53, continuing to get closer to pre-fire conditions. Zone 2 again showed the most signs of recovery (mean = 0.55), followed by Zone 3 (mean = 0.53), and Zone 1, which showed the lowest signs of recovery (mean = 0.49). See Figure 6 for a summary of NDVI results.

A one-way ANOVA was used to test for differences in mean August NDVI among the three proximity zones (Zone 1: mine-adjacent, Zone 2: transitional, Zone 3: Pine Grove). Mean NDVI values were very similar across zones (Zone 1: $M = 0.488$, Zone 2: $M = 0.554$, Zone 3: $M = 0.527$), and the ANOVA indicated no significant effect of zone on NDVI, $F(2, 9) = 0.02$, $p = 0.980$. The between-groups sum of squares (SS = 0.00094) accounted for only about 0.4% of the total variance ($\eta^2 \approx 0.004$), indicating a negligible effect size. Across the four-year August time series, average NDVI does not differ appreciably at the zonal scale, suggesting that late-summer greenness has recovered to broadly comparable levels across the burn perimeter despite differences in disturbance history and proximity to the Zortman–Landusky mines.

The zonal means, however, smooth over finer-scale heterogeneity within zones. A necessary but unfortunate consequence that does not account for the burn perimeter

encompassing multiple forest and rangeland types, differences in canopy cover gradients, and pronounced differences in elevation and aspect. Recovery trends for north-facing, higher-elevation stands would reasonably differ from south-facing, lower-elevation stands and open woodland or grass-shrub communities. This aggregate metric, while observing broad-scale patterns, fails to address the finer-scale differences in vegetation composition, structure, and topography.



	16-Aug-20	16-Aug-21	16-Aug-22	16-Aug-23
NDVI Zone 1	0.727	0.367	0.438	0.488
NDVI Zone 2	0.724	0.32	0.498	0.554
NDVI Zone 3	0.678	0.339	0.478	0.527
NDVI Burn_Area	0.704	0.338	0.477	0.529

Figure 6: Mean NDVI values by zone and year (2020-2023).

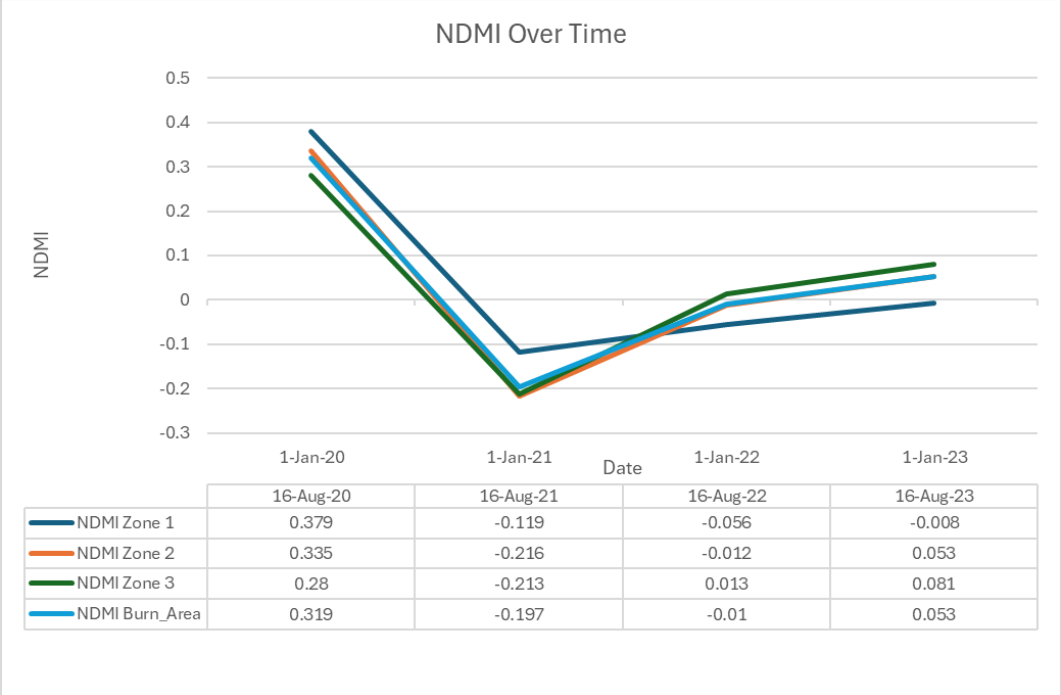
NDMI Time-Series Analysis

Moisture Conditions and Recovery Correlations

NDMI Analysis revealed parallel but distinct trends relative to NDVI, highlighting the role of moisture availability in post-fire recovery. Pre-fire NDMI (2020) mean values ranged from 0.28 (Zone 3) to 0.38 (Zone 1), with Zone 2 in between (mean = 0.34), consistent with

semi-arid vegetation. Post-fire NDMI (2021) dropped sharply to -0.22 (Zone 2) to -0.12 (Zone 1), with a Zone 3 NDMI (mean =-0.21) close in value to Zone 2, reflecting the widespread canopy loss and soil desiccation.

During early recovery (2022) NDMI values increased steadily ranging from -0.06 (Zone 1) to 0.01 (Zone 3), with Zone 2 in between (mean = -0.01), the highest readings occurring on the north-facing slopes and in riparian zones. By 2023, NDMI in the burn area rose to an average of 0.05, remaining well below pre-fire levels. The NDMI data (Figure 7) suggest that Zone 3 exhibits the highest moisture retention recovery over the study period, while being the furthest from disruptions caused by historical mining, and being near present-day anthropological disturbances like the Pine Grove Community.



	16-Aug-20	16-Aug-21	16-Aug-22	16-Aug-23
NDMI Zone 1	0.379	-0.119	-0.056	-0.008
NDMI Zone 2	0.335	-0.216	-0.012	0.053
NDMI Zone 3	0.28	-0.213	0.013	0.081
NDMI Burn_Area	0.319	-0.197	-0.01	0.053

Figure 7: Mean NDMI values by zone and year (2020-2023)

A one-way ANOVA was used to test differences in mean August NDMI among the three proximity zones (Zone 1: mine-adjacent, Zone 2: transitional, Zone 3: Pine Grove). Mean values were very similar across zones (Zone 1: $M = 0.049$, Zone 2: $M = 0.040$, Zone 3: $M = 0.0403$), and the ANOVA indicated no significant effect of zone, $F(2, 9) = 0.00$, $p = 0.998$. The between-groups sum of squares (SS = 0.00021) accounted for only about 0.05% of the total variance ($\eta^2 \approx 0.0005$), indicating a negligible effect size. Thus, for this four-year August time series, average NDMI does not differ appreciably among the mine-adjacent, transitional, and Pine Grove zones, suggesting broadly similar late-summer moisture conditions across the burn perimeter. Correlation analysis between NDVI and NDMI for each Zone for 2020-2023 yielded Zone 1 R^2=0.99, Zone 2 R^2=0.99, and Zone 3 R^2=1.00 suggesting a very strong positive correlation between vegetation greenness and moisture content during recovery for each Zone. These findings align with results from Sagynbayeva et al. (2023), who noted that NDVI-NDMI coupling effectively tracks both canopy regrowth and underlying moisture dynamics.

Topographic and Spatial Patterns

Topography observations suggests it exerts strong control on both burn severity and post-fire vegetation recovery across the Pine Grove Fire perimeter. The burn spans a large swathe of terrain in the Little Rocky Mountains, including steep upper slopes, ridgelines, and concave drainage bottoms. Qualitative analysis of the burn area (Figures 8 & 9) suggests that steeper mid- and upper slopes tend to coincide with areas of higher burn severity and slower vegetation recovery, while gentler lower slopes and valley bottoms generally support higher post-fire NDVI and NDMI values by 2022–2023. These patterns are consistent with greater exposure to wind

and solar radiation, enhanced erosion, and shallower soils on steep, convex landforms, contrasted with deeper, more mesic soils and greater organic material accumulation in concave landforms.

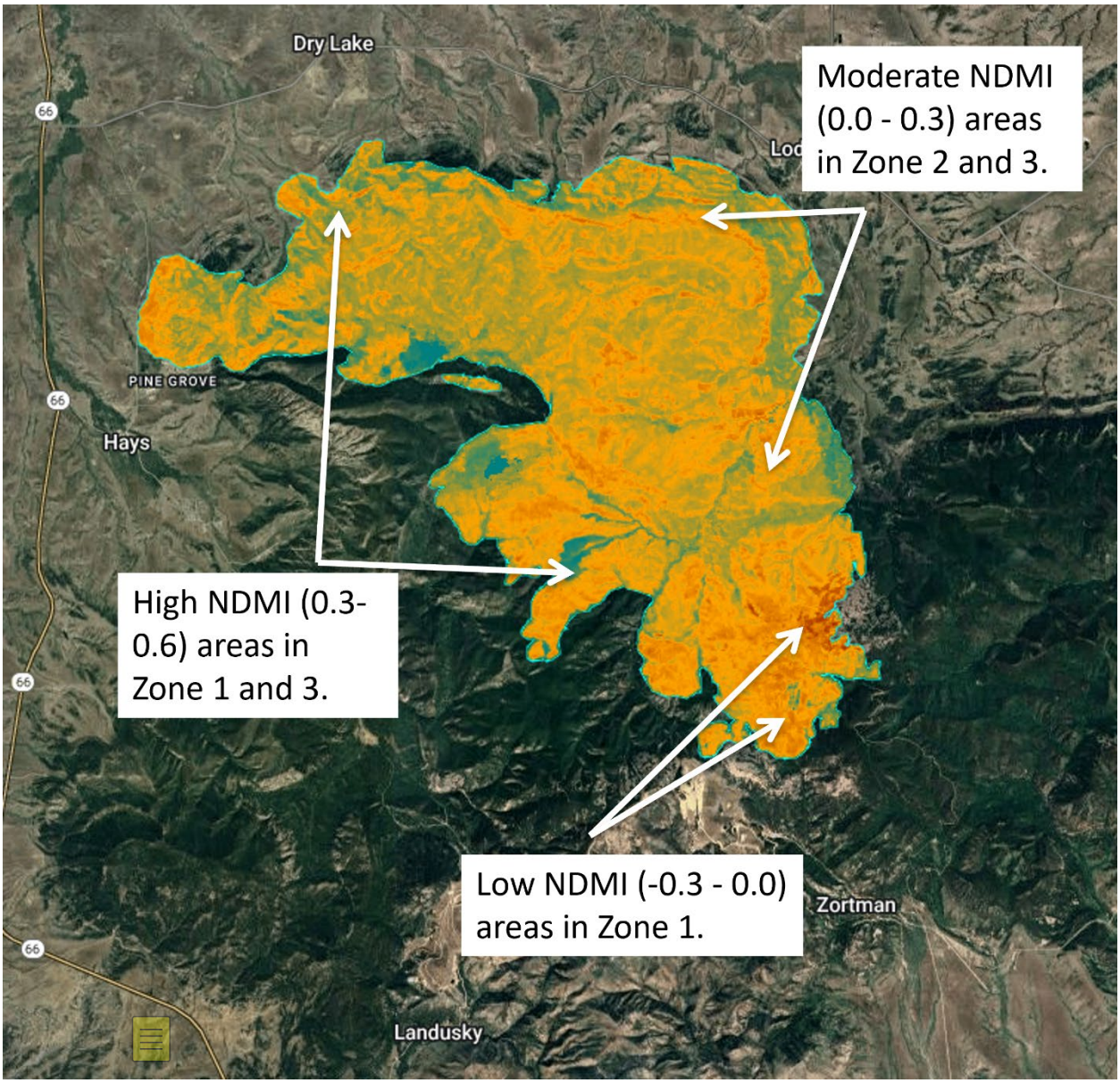


Figure 8. NDMI image of August 2023 Composite.

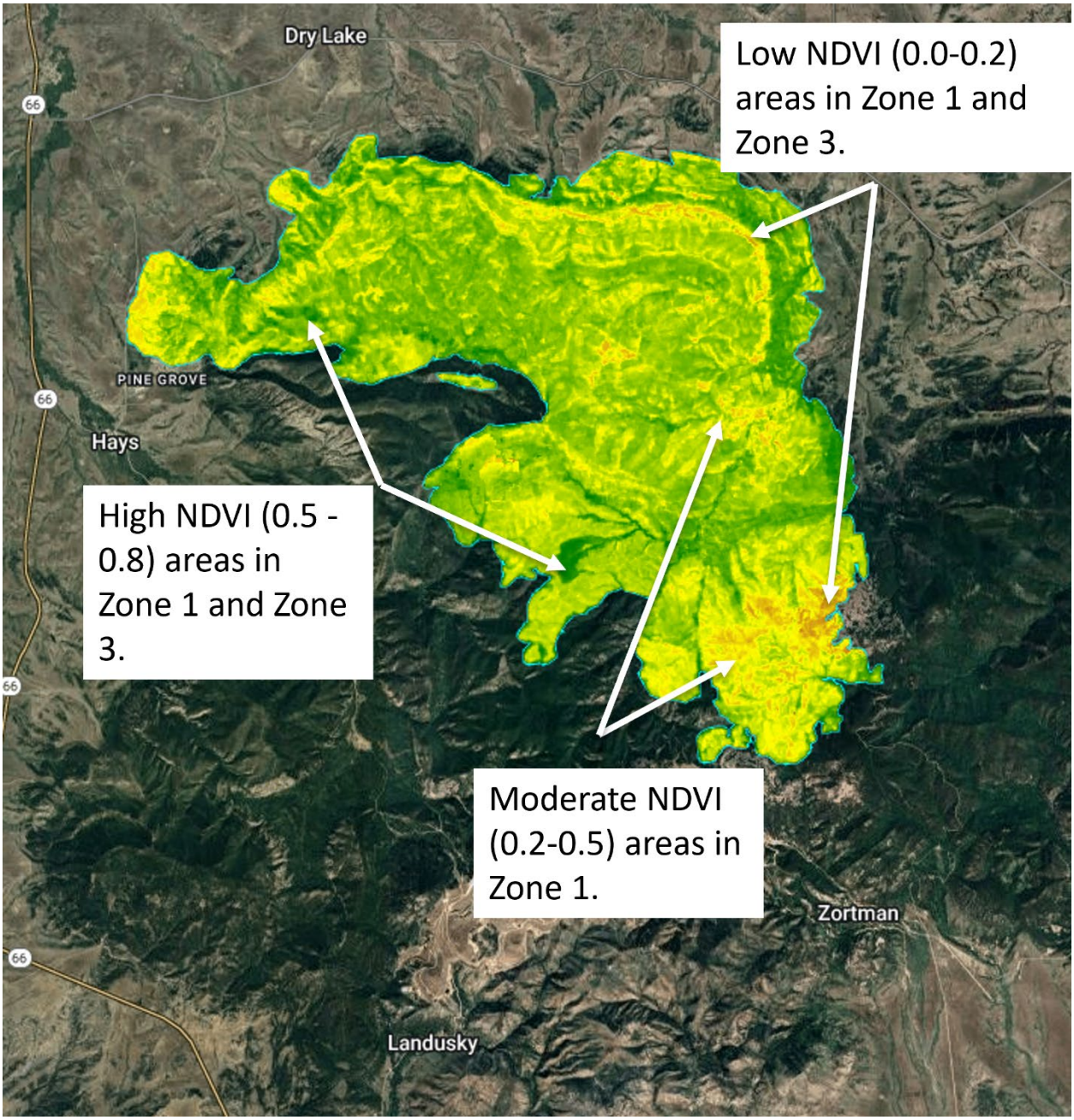


Figure 9. NDVI image of August 2023 Composite.

Aspect further modulates recovery patterns. South- and west-facing slopes, which receive higher solar radiation and experience warmer, drier microclimates, exhibit relatively lower NDVI and NDMI compared to north- and east-facing slopes at similar elevations. In contrast, north-

facing and sheltered slopes tend to retain higher moisture and support more persistent shrub and grass cover, functioning as refuge during the fire and a starting point for post-burn regrowth. These moisture and shading effects are also reflected in the PCA, where PC3 captures subtle gradients associated with slope orientation, topographic shadowing, and local moisture conditions superimposed on the broader vegetation and substrate gradients represented by PC1 and PC2.

Upon observation, the burn perimeter exhibits a clear north–south gradient structured by proximity to the former Zortman–Landusky mine complex. Zone 1, in the southern, mine-adjacent portion of the perimeter, includes steep, exposed slopes and heavily disturbed substrates. PCA outputs and dNBR values indicate a greater prevalence of areas that support the presence of greener vegetation in cooler/moister or shaded positions. And a relatively large area serving as an example of this in the northwest portion of the Zone crossing into Zone 2 as well. Zone 2, the transitional middle band between the mines and Pine Grove, presents a heterogeneous mosaic of spectral responses. Some portions of Zone 2 resemble the disturbed spectral signature of Zone 3, while others align more closely with the greener, more recovered conditions characterized in Zone 1, reflecting mixed slope positions, aspects, and disturbance histories.

Zone 3, in the northern portion of the fire near the Pine Grove community shows a mosaic of recovery patterns, like Zone 2, with large stretches of burned ground along the northern border of the burn perimeter and along the northeastern border near the Lodge Pole community, and more continuous pre-fire forest, exhibits stronger vegetation signatures in the PCA components across much of the area. This zone is dominated by recovering rangeland,

shrub cover, and residual forest patches, indicating more robust post-fire regrowth where substrates are less heavily altered and topographic conditions are more favorable. However, when averaged at the zone scale, one-way ANOVAs showed no statistically significant differences in mean August NDVI or NDMI among Zones 1, 2, and 3 over the 2020–2023 period. This suggests that, by late summer, broad-scale greenness and moisture conditions have largely converged across the burn perimeter, and that the most meaningful differences occur at finer spatial scales. In other words, the topographic and spatial signal in this study is patch-based rather than strictly zonal: localized combinations of steepness, aspect, drainage position, and proximity to mine-impacted substrates govern where recovery lags or accelerates within the overall burn scar.

Principal Component Analysis Results

PCA was successfully applied to the multi-temporal Landsat dataset, enhancing the separability among land-cover classes. The first three components explained 99.38% of the total spectral variance (Figure 10):

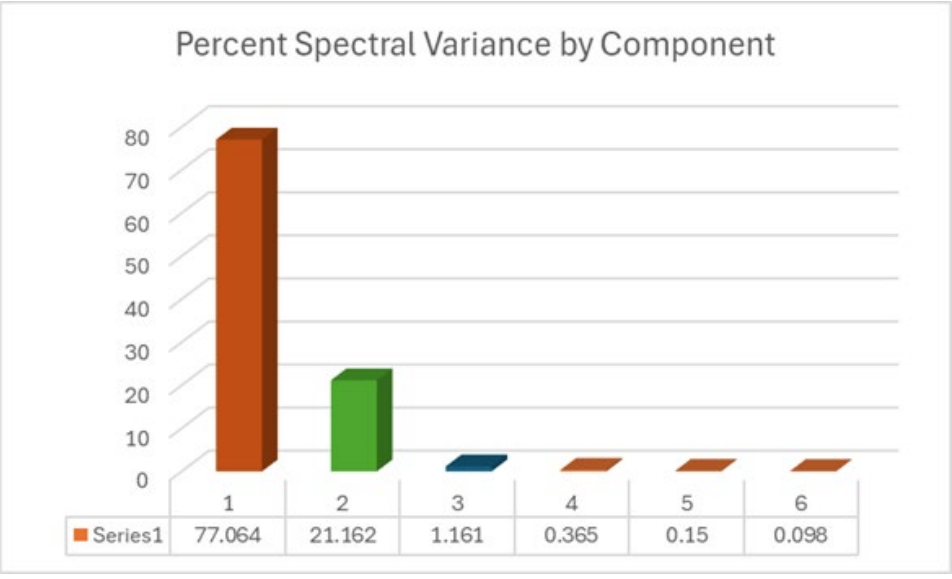


Figure 10. Percent spectral variance by component scree chart.

- PC1 (77.06%) captured overall vegetation and greenness gradients,
- PC2 (21.16%) reflected soil exposure and burn severity,
- PC3 (1.16%) corresponded to moisture and topographic shadow effects.

The PCA output image (Figure 11) shows areas near Zortman-Landusky mines exhibited persistent barren or sparsely vegetated surfaces, whereas central and northern portions of the fire perimeter showed increasing transitions to rangeland and shrub regrowth classes between 2021 and 2023. Within the PCA output image:

- Reddish/pink areas: High PC1 → relatively dense, green vegetation (higher NDVI), more recovered forest/rangeland.
- Bright green areas: High PC2 → exposed or bright substrates: severely burned ground, bare soil, roads, or mine-disturbed areas.
- Bluish/cyan areas: High PC3 → moister or shaded terrain: north-facing slopes, drainages, riparian pockets where moisture/topographic shadow is strong.
- Yellow/orange (red + green, low blue) → vegetated but with more exposed soil or patchy cover (recovering shrub/rangeland on sunnier slopes).
- Magenta/purple (red + blue, low green) → greener vegetation in cooler/moister or shaded positions (north-facing ravines with recovering cover).

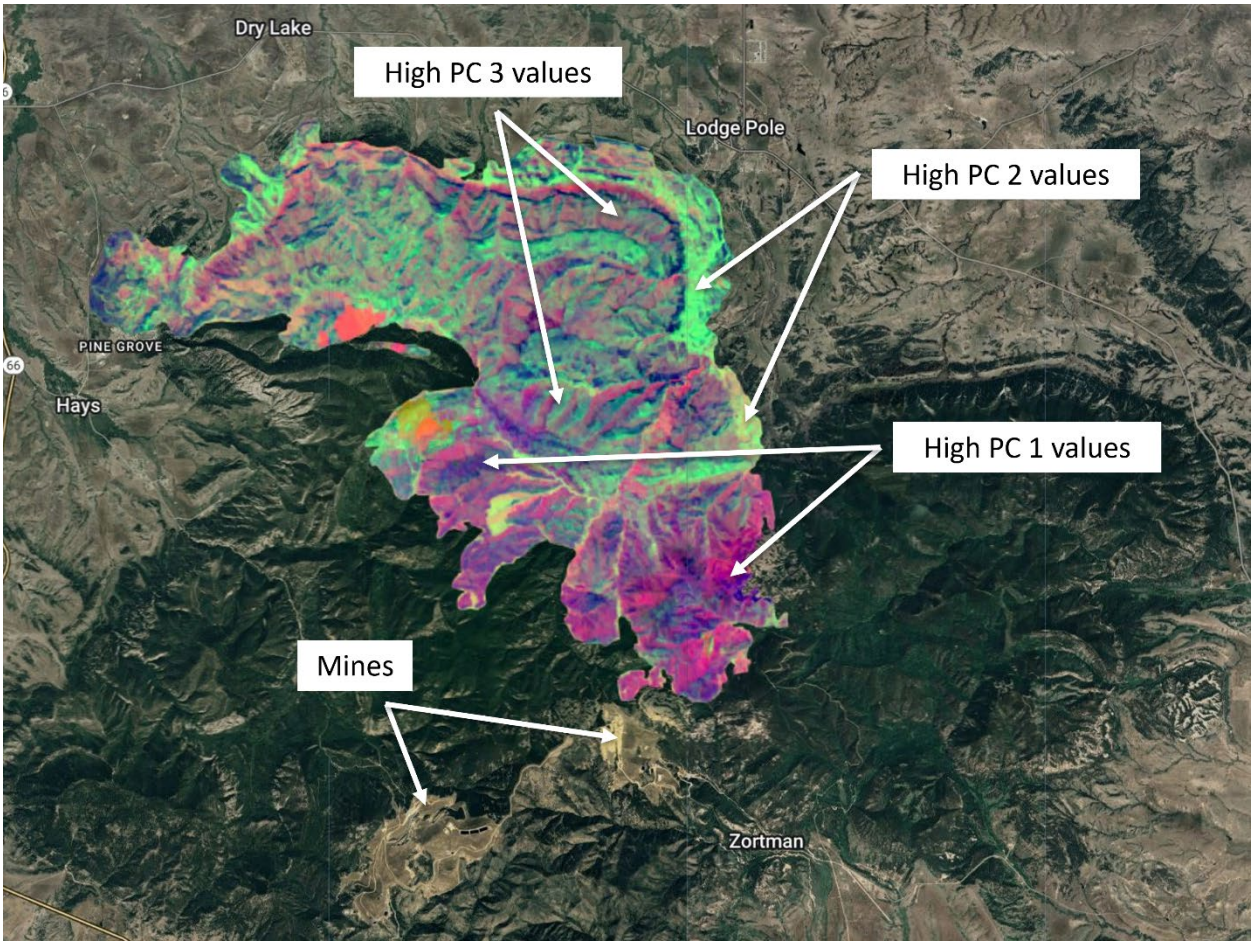


Figure 11: PCA output image, showing the PC distribution across the composite image of August 2020-2023.

Zonal Comparison Summary

Zonal analysis of the Pine Grove Fire burn perimeter shows both shared recovery trajectories, with little variance in recovery rates at the zonal scale for the three proximity zones. Before the fire (August 2020), NDVI values were relatively high across all zones (mean ≈ 0.70 for the burn area), indicating moderately dense forest and rangeland cover. Zone 3 (Pine Grove) and Zone 1 (mine-adjacent) both exhibited comparatively high pre-fire NDVI, suggesting healthy vegetation despite differing disturbance histories. Immediately after the fire (August

2021), NDVI and NDMI declined sharply in all zones, reflecting widespread canopy loss and soil exposure. Zone 1 had the highest NDVI value (mean=0.37). Zone 2 (transitional) recorded the lowest NDVI (mean=0.32), while Zone 3 retained slightly higher residual greenness (mean=0.34), consistent with partial survival of vegetation along the perimeter and in less severely burned patches. NDMI values were comparable in Zones 2 and 3 (mean=-0.21 in both zones), and "highest" in Zone 1 (mean=-0.12).

During the early recovery phase (2022), NDVI and NDMI values increased across the burn area, with regrowth concentrated in lower-slope positions and on cooler, north-facing aspects. Zone 2 showed the highest NDVI (mean=0.50), followed by Zone 3 (mean=0.48), while Zone 1 continued to show recovery but had the lowest value (mean=0.44). NDMI showed the most recovery in Zone 3 (mean=0.01), followed by Zone 2 (mean=-0.01), and Zone 1 (mean=-0.06).

During the recovery year of 2023 NDVI values continued to increase with Zone 2 having the highest value (mean=0.55), followed by Zone 3 (mean=0.53), and Zone 1 (mean=0.49). NDMI values continued to recover with Zone 3 showing the most recovery for this period (mean=0.053), followed by Zone 2 (mean=0.05), and Zone 1 (mean=-0.01). NDVI and NDMI were averaged across the full 2020–2023 August time series, one-way ANOVA results indicated no statistically significant differences in mean NDVI or NDMI among the three zones, and effect sizes were negligible. This implies that, at the broad zone scale, late-summer greenness and moisture have largely converged, even though local site conditions still matter.
Topographic and PCA-based observations clarify this apparent contradiction. Terrain observations shows that steep, south-facing, slopes host more persistent high-severity and low-

recovery patches, whereas gentler slopes, drainage bottoms, and north-facing aspects that favor faster regrowth. PCA components highlight these patterns by consistently mapping barren or sparsely vegetated surfaces near the Zortman–Landusky mines and more extensive rangeland and shrub recovery in central and northern parts of the perimeter. Strong NDVI–NDMI correlations in all zones indicate that moisture availability is a key control on regrowth everywhere. Overall, the zonal comparison suggests that legacy mining minimally influences recovery of the burn area, with recovery resistance strongly asserting itself at the patch and hillslope scales, while zone-averaged vegetation and moisture conditions have begun to rebound toward similar late-summer states across the burn area.

Summary of Findings

1. Vegetation recovery is ongoing but incomplete, as NDVI values in 2023 approach but do not yet reach pre-fire levels.
2. Proximity to mining sites does not significantly reduce recovery rates, as indicated by ANOVA results.
3. Moisture availability and topographic position observations strongly influence regrowth, with north-facing and low-slope areas recovering fastest.
4. PCA-enhanced analysis improved classification accuracy and confirmed the presence of persistent barren zones near the Zortman-Landusky Mines.
5. The results align with previous studies that NDVI and NDMI are effective metrics for long-term post-fire monitoring (Liu et al., 2023;Sagynbayeva et al., 2023; Tonbul et al., 2016).

6. Temporal and spatial analyses reveal that the Pine Grove Fire recovery has been heterogeneous, mainly influenced by natural environmental factors, and potentially limited anthropogenic effects at patch scale near the former mines.

DISCUSSION

Vegetation Recovery Patterns and Dynamics

The NDVI time-series analysis revealed substantial vegetation recovery across the Pine Grove Fire burn Area between 2021 and 2023, with no distinct spatial variability related to proximity to the mine. Observed patterns of recovery near the mine sites do not align with studies demonstrating that soil contamination, altered hydrology, and reduced nutrient availability can inhibit post-fire vegetation regeneration (Tonbul et al., 2016; Perez-Cabello et al., 2021). Zones farther from the mines, in contrast, particularly those near Pine Grove, tended to exhibit slightly higher NDVI and NDMI values over the same period, due to more favorable soil and moisture conditions. The overall recovery, as indicated by the burn area NDVI post-fire (0.34) to 2023 (0.53), suggests significant regrowth but incomplete canopy recovery, particularly in areas that experienced higher burn severity.

These findings are consistent with Sagynbayeva et al. (2023). Researchers have found that forest regeneration following fire in semi-arid pine ecosystems can take multiple years to return to pre-fire vegetation density, especially in areas with limited soil conditions. Liu et al. (2023) reported that recovery trajectories in semi-arid regions are strongly influenced by moisture availability and local climate gradients, factors also evident in the microclimatic variability of the Little Rocky Mountains.

Moisture Availability and Climatic Influences

Observation of the of the 2023 composite NDMI results indices suggest that post-fire recovery was closely tied to moisture conditions. With indices recovering at a faster rate in riparian areas, drainages, north and eastern facing slopes, and in areas that experienced less burn severity.

Climate data from Hays, Montana, indicate that limited summertime precipitation (averaging 1.2 inches in August) and moderate humidity (~44%) may have constrained vegetation reestablishment during the first two growing seasons following the fire, as persistent drought conditions were reported across Montana during 2021-2022 (Great Falls Tribune, 2021), likely to exacerbate these effects and reinforcing the need for moisture-focused management strategies, such as reseeding, mulching, and targeted erosion control in severely burned zones. This aligns with Perez-Cabello et al. (2021), who found that drought stress and reduced soil moisture significantly delay post-fire vegetation regeneration, particularly in continental climates like north-central Montana.

Topographic and Terrain Effects

The influence of topography on recovery was also notable. Recovery was strongest on north- and east-facing slopes and in lower elevations where microclimatic conditions favored moisture retention. This observation aligns with the findings of Tonbul et al. (2016), who observed similar slope-dependent recovery patterns in Mediterranean environments.
Steeper, south-facing slopes exhibited lower recovery. These slopes tend to experience higher exposure rates to solar radiation and increased desiccation rates, leading to further impaired recovery. The DEM-based analysis suggests that slope is strongly related to NDVI, underscoring the role of terrain in shaping recovery heterogeneity.

From a management perspective, this suggests that restoration actions may be most effective when prioritized for high-severity burns, or steep south-facing slopes, and mine-adjacent zones.

Influence of Legacy Mining Activities

Perhaps the most striking finding of this analysis is that proximity to the former mining sites did not produce statistically significant differences were detected among zones in mean NDVI and NDMI. Across all the post-fire years, NDVI and NDMI values were not significantly lower within two kilometers of mines compared to other zones.

Several mechanisms are likely to contribute to the localized non-recovery observed in mine-adjacent patches, even though zone-averaged NDVI and NDMI are not significantly different.

1. Soil and Water Contamination: Acid mine drainage and heavy metal accumulation (e.g., arsenic, lead, and zinc) can inhibit root development and limit nutrient uptake.
2. Altered soil pH and Structure: Historical heap leaching and surface disturbance from mining have degraded soil composition and permeability, reducing water infiltration.
3. Vegetation Stress Legacy: Pre-existing stress on vegetation before the fire, as evidenced by the lower pre-fire NDVI, may have compounded post-fire regeneration challenges.

These patch-level patterns align with research demonstrating that post-mining landscapes often require intervention for vegetation recovery due to long-term alterations in soil and hydrological processes (Perez-Cabello et al., 2021; Liu et al., 2023). The persistence of barren or sparsely vegetated surfaces near the mine complex (as seen in observation of the NDVI) suggests that natural recovery may be insufficient on its own to restore these areas to their pre-fire condition.

Integration of Remote Sensing and PCA Approaches

The use of multi-temporal NDVI, NDMI, and PCA analyses proved highly effective in quantifying post-fire recovery patterns across non-homogeneous terrain in the Little Rocky Mountains. The PCA provided improved discrimination between recovering vegetation and persistently barren areas, consistent with the findings of Ghouzlane & Fistikoglu (2024). By reorienting the spectral data along axes of maximum variance, PCA reduced noise and highlighted ecological gradients in vegetation regrowth.

This integrative approach demonstrates the value of combining NDVI and PCA for post-disturbance assessment, especially when working with medium-resolution satellite imagery such as Landsat-8. Furthermore, the methodology developed in this study, utilizing GEE, can offer a cost-effective and reproducible framework for other researchers and land managers.

Comparative Evaluation with Previous Studies

The patterns observed in the Pine Grove Fire recovery align with global trends in semi-arid post-fire recovery, but they also highlight unique local constraints. As noted in Sagynbayeva et al. (2023), recovery in pine ecosystems is highly dependent on pre-fire stand structure and soil conditions. Additionally, Liu et al. (2023) found that NDVI recovery in semi-arid zones tends to plateau after three years unless assisted by restoration measures.

In contrast, the Pine Grove analysis suggests that recovery may continue at a slower but steady pace beyond 2023, given the positive trajectories of NDVI and NDMI. Mine-adjacent areas may, however, remain barren without targeted remediation due to ongoing soil and hydrological limitations.

These findings highlight the importance of considering localized context, including legacy land use, hydrology, and cultural management practices such as planting/harvesting of native species and harvesting of timber for building and heating, when interpreting remote sensing results.

Management Implications and Recommendations

The integration of remote sensing, climate, and topographic analyses offers valuable perspectives for ecosystem management on the Fort Belknap Indian Reservation and adjacent BLM lands. Based on this, several recommendations can be made:

1. Targeted Restoration Near Mine Sites: Areas within 2 km of the Zortman-Landusky mines should be prioritized for active revegetation, including but not limited to soil amendments and reseeding with native species tolerant of low pH and heavy metal contamination.
2. Erosion and Hydrology Management: Implement erosion control and hydrological restoration in steep and highly eroded slopes to enhance moisture retention and reduce runoff that may mobilize residual contaminants.
3. Long-term Monitoring: Continued NDVI and NDMI monitoring using GEE and Landsat-8 imagery, providing cost-effective annual updates on vegetation recovery trends.
4. Integration of Indigenous Ecological Knowledge: Collaborate with the Fort Belknap Indian Community to incorporate Traditional Ecological Knowledge (TEK) into restoration planning, particularly regarding species selection and stewardship practices.
5. Adaptive Management Framework: Use the findings to inform adaptive management strategies that integrate remote sensing data, field validation, and community-based decision-making to guide recovery efforts for future fire events.

Study Limitations

While the study presents robust spatial and temporal insights, several limitations need to be acknowledged.

- Resolution Constraints: The 30-meter resolution of the Landsat-8 imagery may not capture fine-scale heterogeneity in vegetation regrowth, particularly along riparian corridors and patchy regrowth zones.
- Limited Ground Validation: Field data were limited due to access restrictions and logistical constraints; future efforts should include systematic ground truthing to validate spectral indices.
- Climatic Variability: Short-term drought events or above-average rainfall in specific years may influence NDVI/NDMI trends, introducing temporal variability that is not fully accounted for within the four-year time frame observed in this study.
- Chemical Soil Data: The lack of site-specific soil chemistry data near the mine complex limits direct attribution of reduced NDVI to impacted soil quality versus other factors such as slope and aspect.

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