Environmental Degradation and Health Disparities in Central Appalachia: The Legacy of Surface Coal Mining

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18 April 2025

Research Design in Environmental Studies

ENST 2097

Temple University

Philadelphia, PA

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Abstract

Surface coal mining has shaped Central Appalachia's landscape and economy for centuries, but it has also led to lasting environmental degradation and public health disparities. This study examines the environmental and health impacts of surface coal mining, specifically topographic disruption, water contamination, and elevated disease rates. Then, using GIS-based suitability modeling, this research identifies both areas that are at highest risk to the adverse impacts of surface coal mining, and areas in which targeted reforestation would be most beneficial. Findings show that mining-related risks can be geographically concentrated, and that restoration strategies combining reforestation, soil reconstruction, and wetland creation offer the greatest potential for ecological and community recovery. These results emphasize the need for restoration efforts that prioritize both environmental and social recovery through spatially informed strategies.

Keywords: Surface Coal Mining, Central Appalachia, Ecology, Environmental Equity, Public Health

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Introduction

For centuries, coal has shaped the landscape, economy, and communities of Central Appalachia, but its legacy extends much further than the mines themselves. The Appalachian Mountains, among the oldest mountains on earth, stretch from northern Alabama into Canada, forming a geographic and cultural backbone up the eastern United States. Historically, coal mining has been the largest industry in Appalachia. The Appalachian coalfield spans seven U.S. states and has made coal extraction a central force in the region's development (Zipper et al. 2021, 2). Among the most impacted states are Kentucky, Ohio, Pennsylvania, and West Virginia, the latter almost entirely encompassed by the coalfield. Coal mining has historically powered transportation, salt and steel manufacturing, energy, and electricity generation (Zipper et al. 2021). Despite the influential role it has had on Central Appalachia, existing research has shown that the coal industry, specifically surface coal mining practices, contributes to lasting environmental and public health consequences in this region.

The most common method of surface coal extraction in Central Appalachia is mountaintop removal mining. This process begins with the logging of existing trees, followed by the use of explosives and heavy machinery on shallow pockets of coal, often just a meter thick (Ross et al. 2016, 2064). After extraction, the coal is transported to a nearby preparation plant, and the remaining blasted waste, or "spoils", is either used to rebuild the blasted area or dumped into neighboring valleys. This dramatic topographic change loosens soils and destabilizes the terrain, leading to hydrologic alterations and contamination of local water sources. Runoff from these spoils displaced into valley fills often enters headwater streams, introducing harmful trace elements, major ions, or selenium (Ross et al. 2016, 2065). These contaminants can have adverse effects on aquatic ecosystems, particularly low-order macroinvertebrates such as aquatic insects, and pose risks to human health due to contaminated drinking water.

The environmental deterioration caused by surface coal mining has lasting consequences on the human health of surrounding communities. The entire coal extraction process, from removal to processing and waste disposal, contributes to environmental contamination that leads to severe health outcomes. More than one million people reside in counties where mountaintop removal mining occurs, and studies have consistently linked this population with elevated rates of cardiovascular, kidney, respiratory, and dental diseases, as well as cancer (Hendryx et al. 2020, 401). Additionally, recent research has linked airborne contaminants from surface mining operations to increased adverse pregnancy outcomes like preterm birth (PTB) and low birthweight (LBW) (Ruktanonchai et al. 2022). Despite the extremity of these risks, current remediation efforts in this region often fail to prioritize the needs and perspectives of the affected communities. Moving forward, mitigation and restoration projects should emphasize meaningful collaboration with the residents at risk to fully address the extent of these public health challenges.

In response to the environmental and public health consequences of surface coal mining, efforts to both mitigate damage and restore impacted landscapes have gained attention but remain limited in scope. The Surface Mining Control and Reclamation Act (SMCRA), passed in 1977, legally mandates all former mines to take part in restoration efforts once the mining activity concludes (Thomas et al. 2023, 1). One of the most widely used restorative practices is referred to as the Forestry Reclamation Approach (FRA). Through soil decompaction and tree planting, reforestation using both native and non-native species can provide great benefits to both the environment and the surrounding communities (Skousen et al. 2018). Coupling FRA techniques with wetland creation has proven effective in both acting as soil filtration systems and restoring amphibian habitat (Sherman et al. 2024, 13).

To better inform where these restoration efforts should be prioritized, this paper incorporates a risk assessment and site suitability analysis using GIS software. This analysis aims to identify areas at highest risk from the adverse effects of surface coal mining and determine the most suitable areas for targeted restoration. The risk analysis will look at seven distinct factors pertaining to vulnerability and public health, along with proximity to mines and hydrologic features. The site suitability builds upon these results by considering at-risk areas with proximity to closed mines, land cover, and topography to evaluate the long-term feasibility of reforestation. Given the scale of environmental degradation and health disparities in Central Appalachia, this paper investigates the spatial relationships between environmental harm, public health risks, and restorative land use potential, ultimately identifying the communities most impacted and the areas most suitable for targeted reforestation.

Research Question

How does surface coal mining in Central Appalachia impact the environment and public health, and what mitigation strategies can address these effects?

Literature Review

Central Appalachia contains some of the most coal-rich regions in the United States, which causes surface mines to concentrate in these areas. Surface coal mining in Central Appalachia has dramatically altered the region's landscape, hydrology, and public health outcomes. The existing literature surrounding this topic highlights the environmental impacts of mining, particularly hydrologic contamination from mine runoff and the destruction of riparian ecosystems. These impacts have been linked to significant public health disparities, including respiratory illnesses, cancer, and waterborne diseases found in communities near mines. Although some measures have attempted to mitigate these effects, challenges persist in both environmental restoration and the protection of vulnerable populations. This literature review examines the environmental impact of surface coal mining in Central Appalachia, its contribution to public health disparities, and evaluates strategies such as reforestation and wetland creation to support recovery. Through reviewing existing literature, this section establishes a solid foundation for further understanding the extent of this issue and identifying pathways towards remediation.

1. Environmental Impacts

Surface coal mining in Appalachia is primarily conducted through mountaintop removal and valley filling methods. This process begins with large-scale deforestation, followed by the demolition and explosion of mountaintops through blasting, and ends with the disposal of rock spoils into adjacent valleys. An inherently destructive practice, surface coal mining both destroys the surrounding ecosystems and permanently alters the region's topography. These physical transformations result in a variety of adverse environmental effects, including degraded water quality, disrupted hydrologic systems, and an overall loss of biodiversity extending far beyond the immediate mining area.

1.1 *Topographic Disruption*

Mountaintop removal mining and consequent valley filling methods fundamentally reshape the terrain of Central Appalachia, lowering elevations and altering slope in irreversible ways. According to Pericak et al., mining in the Appalachian coal field has decreased the average slope by approximately ten degrees, which is vastly different than the natural steep landscape of Appalachian areas (2018, 2). The researchers claim that the flattening of the terrain represents a major disruption to the region's landscape, as the steep slopes typical of the Appalachians play a critical role in directing water flow, maintaining soil stability, and overall maintaining environmental equilibrium in this area. By reducing slope, mountaintop removal mining both erases the physical identity of this area and disrupts the natural processes that depend on this specific terrain. The reduction in average slope also reflects the impact of valley filling, a practice in which steep valleys are filled with mining spoils. Together with the leveling of mountaintops, this process creates a drastically more uniform and unnatural topography. This is reinforced by research from Ross et al., who found that a single valley fill resulted in elevation decreases of up to 60 meters from ridge cutting, and elevation gains of up to 95 meters from infilling (2016, 2066). These dramatic changes highlight the extent to which surface mining reshapes the Appalachian landscape from its natural form, leaving behind a topography that is neither ecologically functional nor easily restorable.

While the local impacts of mountaintop removal are striking, the true scale of this topographic transformation becomes even more pronounced when looking at the region. The spatial extent of topographic alteration resulting from surface coal mining spans thousands of square kilometers, with remote sensing and other geospatial tools allowing for more efficient data collection and analysis. Pericak et al. provide research stating that "between 1985 and 2015, an average of 87 km^2 of previously unmined land was converted to a surface mine any given year (2018, 6). This research emphasizes the extent to which surface mining has continued to persist in Central Appalachia. Surface mines are not isolated environmental disturbances, but rather repeated instances of environmentally damaging resource extraction in a demographically vulnerable region. Reinforcing this argument, Bernhardt et al. state that "Central Appalachia has the highest rates of earth movement in the United States, as each surface mine generates large quantities of waste rock" (2012, 8115). This long-term, large-scale trend illustrates how surface mining has persisted in being a primary driver of landscape change in Central Appalachia, gradually replacing the ancient, complex mountainous terrain with unnaturally modified plateaus and fills.

1.2 *Hydrologic Disturbance*

The dramatic topographic change caused by surface coal mining in Central Appalachia has direct effects on the connected watersheds. The removal of entire ridgelines and the subsequent displacement into adjacent valleys disrupt natural soil compaction and often bury headwater streams under hundreds of meters of loose rock. These streams play a crucial role in collecting and filtering runoff, supplying communities with water, and supporting downstream ecosystems. According to research conducted by Lindberg et al., the burial of these headwater streams leads directly to trace elements being found in the watershed (2011, 20929). High trace element concentrations are combatted by the artificial placement of cations, but Lindberg et al. states that this technique leads to "elevated pH, electrical conductivity, and concentrations of total suspended solids compared to reference streams" (2011, 20929). Lindberg et al. argue that these unnatural topographic disruptions caused by surface mining have direct consequences for both the immediate and downstream environment, affecting wildlife, aquatic ecosystems, and human communities alike. These findings highlight how the excess material from surface mining fundamentally disrupts local water quality by altering flow and introducing chemical contaminants. The burial of headwater streams and the disruption of natural drainage networks compromise the environmental integrity of Central Appalachia, affecting both the surrounding ecosystems and human communities.

The degradation of water quality caused by stream burial and spoil runoffs consequently affects aquatic ecosystems, particularly through the disruption of riparian food webs and the loss of biodiversity downstream. The acid mine drainage caused by displaced rock spoils causes a major increase in selenium, trace elements, and/or major ions in nearby streams (Ross et al. 2016). These contaminants directly affect lower order macroinvertebrates such as crayfish and aquatic insects, but via biotransfer it can be passed to higher order consumers like birds and bats (Clark et al. 2023, 2663). In other words, the increased presence of trace elements and major ions directly affects the structure and stability of aquatic food webs by weakening lower-order organisms and contaminating organisms higher up the trophic chain. These findings demonstrate how mining-induced water pollution can extend far beyond immediate stream health. Further research conducted by Naslund et al. identified that "at 79% of all sites, average Se concentrations in adult insects from mined sites were 5 times higher than those at unmined stream," and that these concentrations exceeded the bird dietary risk threshold at most impacted streams (2020, 3955). This evidence reflects the persistence and severity of Se contamination in aquatic food systems, as well as its ability to accumulate within higher-order species across ecosystems. In turn, the ecological effects of mining runoff pose long-term risks not only to aquatic ecosystems, but to terrestrial wildlife and broader species within Central Appalachia. These disruptions highlight how surface coal mining directly decreases biodiversity and increases ecosystemic pressure that extends well beyond mined sites.

2. Public Health Disparities

The same environmental disruptions that degrade the topography and hydrology of Central Appalachia also pose serious risks to human health, especially in communities that depend on local surface and groundwater sources for drinking, bathing, and other daily uses. Every stage of the coal extraction and use process- including extraction, processing, use, waste, and power generation- contributes to adverse health outcomes. Approximately 1.2 million people live in counties where mountaintop removal mining occurs, and research by Hendryx et al. has shown that residents in these areas experience elevated rates of cardiovascular, kidney, respiratory, and dental disease, as well as cancer (2020, 401). These conditions are linked to both air and water contamination, including airborne particulate matter concentrations and trace element concentrations of local watersheds. In addition to these health risks, Central Appalachian communities often face limited access to data and resources regarding safe drinking water, which can lead to misinformation and distress. A study by Krometis et al. found that in West Virginia's Mingo and Wyoming counties, many residents believed all local water sources to be unsafe, which led to individuals purchasing bottles of water when they either didn't need to, didn't have the budget to, or both (2022, 259). Residents felt inclined to purchase externally sourced water regardless of their financial capacity or the actual level of contamination present in their local water supply. This reflects not only the material effects of environmental pollution, but also the mental and economic tolls it can take on already vulnerable populations. These risks, both real and perceived, emphasize the broader public health burden associated with surface coal mining.

In addition to chronic illnesses, research has shown that surface coal mining has adverse effects on reproductive health, specifically in the form of adverse birthing outcomes. Existing research regarding adverse birth outcomes caused by surface coal mining identifies both airsheds and watersheds as exposure pathways in Central Appalachia. A case study conducted by Cooper et al. reveals that an association was found between mountaintop removal mining and gastro-intestinal birth defects in infants between 1997-2003 in Appalachian Kentucky (2022, 12). Although Cooper et al. finds significant association between adverse birth outcomes and proximity to mountaintop removal mines, their work could be supported by defining which exposure pathways affect births more. Research from Ruktanonchai et al. directly address this issue, finding that airshed contaminants from surface coal mining activities contribute to both preterm birth and low birthweight, whereas the watershed exposure pathway was less pronounced (2022). This is not to suggest that watershed contamination has no negative effects, as already discussed in the previous paragraph, but rather that adverse birthing outcomes are most affected via the airshed exposure pathway. Collectively, this evidence highlights how airborne pollution from surface coal mining is a critical factor in adverse birth outcomes like preterm birth and low birthweight, emphasizing the importance of addressing airshed exposure when evaluating health risks in Central Appalachia.

3. Mitigation and Restorative Potential

Given the extent to which surface coal mining impacts the environment and public health of adjacent areas, mitigation and restoration should be a priority for Appalachian communities. In areas where mining still occurs more sustainable practices must be implemented to mitigate the immediate impacts, and in areas where mining has since been halted, restoring and repurposing mined lands must be implemented to rebuild the environment. Active surface mines can reduce greenhouse gas emissions by optimizing operational efficiency (OE) and implementing on-site water treatment stations. Closed surface mines can adapt restorative tree planting practices, such as the widely used Forestry Reclamation Approach (FRA), in addition to alternatives such as wetland creation and soil reconstruction. In adapting these mitigative and restorative strategies, affected areas can begin to rebuild ecological function, reduce health risks, and further promote sustainable mining and post-mining practices.

3.1 *Green Mining*

Despite a recent decline in coal demand and production, mining remains a major industry in many Appalachian communities, making blanket restoration of all sites, regardless of operation status, not a viable option. Having said that, active surface coal mines should implement more efficient extraction, processing, and waste removal to limit adverse environmental and public health impacts. Research from Rai et al., conducted on a surface coal mine in India, found that increasing OE by 40% led to a 26.4% decrease in greenhouse gas, 46.9% decrease in total suspended particulates, and 52.4% decrease in PM_{10} emissions (2020, 38). In other words, Rai et al. found quantifiable proof that improving mine planning and optimizing equipment usage can lead to the broader reduction of harmful emissions by ~25%-50%. In addition to optimizing operational efficiency, active mines, specifically those near streams and rivers, could implement on-site water treatment in order to mitigate hydrologic impacts. A case study by Iepure and Pop on a Romanian mining-influenced area found that introducing iron scrap to acidic mine water both increased pH levels from 2.75 to 4.8 and neutralized the existence of toxic metals like copper, zinc, and cadmium (2025, 8). These researchers point out how the introduction of other safe elements into mine-influenced water can act as a filter for toxic metals, leading to an increase in water quality. Similar treatment methods could be implemented in Central Appalachian mining regions, provided that adjustments are made to account for environmental and operational conditions. Together, these mitigation strategies demonstrate that minimizing harm during active mining is both feasible and essential for reducing the long-term impacts of surface coal mining.

3.2 *Reforestation*

While mitigation strategies aim to reduce the impacts of active mines, restorative efforts like reforestation play a critical role in repairing the damaged landscapes of mined lands. Many mines have adapted the Forestry Reclamation Approach (FRA), which is composed of the following five steps: create a suitable rooting medium for good tree growth, loosely grade the topsoil established in step one to create a non-compacted medium, use less competitive ground covers that are compatible with native trees, plant multiple types of trees, and use proper tree planting techniques (Zipper et al. 2011, 753-755). Although the FRA is widely adopted and surface mine restoration is federally mandated under the SMCRA, many reclaimed sites still fail to achieve long-term, sustainable recovery. Research by Thomas et al. analyzing all Central Appalachian surface mines found that while 98% of post-mining landscapes experienced forest regrowth, only 7.9% recovered to conditions comparable to unmined reference forests (2023, 9). This suggests that while reforestation may be present in the majority of mined lands, it is rarely to an extent that fully restores impacted areas. This is largely due to barriers such as soil compaction and contamination, which inhibits nutrient intake and root development, causing trees to regrow significantly less resilient than those in native forests. Given these limitations, it is essential to explore alternative methods of restoration that can either supplement or substitute areas where reforestation has proved ineffective.

3.3 *Alternative Methods*

Although reforestation does have limitations in this region, supplementing alternative methods like soil reconstruction and wetland creation can yield positive effects both on tree life and broader restorative implications like public health. As mentioned previously, the soil quality in areas where reforestation occurs is a major factor in the health and resilience of trees. Research by Zipper et al. (2013) found that the most suitable soils for reforesting in Appalachian mining regions are those with a slightly to moderately acidic pH and low electrical conductivity (EC). Native soils are ideal for reclamation, but their effectiveness depends on minimizing compaction during replacement, as this allows for proper root growth and nutrient uptake (346). When native soil is unavailable, weathered rock spoils serve as the best alternative, as the natural weathering process causes the spoils to be more similar chemically to native soils, including slight acidity and low EC. In addition to proper soil reconstruction, researchers Sherman et al. (2024) found that integrating wetland creation with the FRA could help both forest growth and habitat reestablishment. They found evidence that coupling wetland creation with the FRA could restore pond-breeding amphibian habitats within ten years of implementation (2024, 13). Restoring habitats for amphibians such as frogs and newts can also improve the health of reforested areas, as wetlands could serve both as natural filters for contaminated water and as a means of increasing biodiversity. By combining soil reconstruction and wetland restoration approaches with the FRA, post-mining landscapes can be rehabilitated in ways to support forest development and promote long-term ecological resilience and community health.

Conclusion

The existing literature makes it clear that surface coal mining in Central Appalachia has heavily altered the region's environment, hydrology, and public health landscape. Research consistently illustrates how topographic change, watershed contamination, and airborne pollution have compounding negative ecological and community impacts. Although mitigation and restoration efforts like soil reconstruction and reforestation have shown promise, challenges like soil compaction and limited community resources highlight the need for more adaptive solutions. Together, these findings establish a strong foundation for spatial analyses aimed at identifying where risk is most prevalent and where reforestation could be most effective.

Data Analysis

Risk Assessment

The existing literature provides valuable insight into the environmental and public health consequences of surface coal mining; however, a spatial analysis could help further clarify where these impacts are most concentrated. To support this, multiple data sources were compiled to perform a GIS-based risk assessment. Demographic and health indicators were extracted at the census tract level, including Social Vulnerability Index (SVI) rank, percentage of the population with asthma, percentage with COPD, Safe Drinking Water Act (SDWA) non-compliance percentile, and the percentage of the population without health insurance. These datasets were downloaded as CSV files from Policy Map, and are sourced from reputable sources like the CDC, U.S. Census Bureau, and EPA. Each indicator is commonly used in environmental justice research and public health assessments, so they fit well within the scope of this research (Frigerio et al. 2016). Additionally, locations of all coal mines in the United States were extracted from Global Energy Monitor, which maintains records of energy infrastructure across the United States. Geographic boundary data at tract and county levels was extracted via the U.S. Census Bureau website to allow data manipulation at multiple levels. Lastly, land use data from the West Virginia GIS Technical Center was used to identify hydrology, streams and rivers specifically, as well as surface mine barrens.

Methodology

All datasets were imported into ArcGIS Pro and projected to the NAD 1983 UTM Zone 17N coordinate system to ensure consistency across layers. This data selection aligns with the paper's primary goal: not only to identify where surface coal mining has occurred, but also to assess where its environmental and health impacts may be most concentrated. The analysis focuses on six counties in southern West Virginia: Raleigh, Boone, Mingo, Wyoming, McDowell, and Logan. This area was determined to have the highest density of surface coal mining activity, which was calculated by dividing the number of mines in a county by the counties' total area. Together, the compiled datasets support both a risk assessment to evaluate environmental exposure and guide restoration efforts. The spatial analysis was structured around three data categories: (1) Vulnerability, measured by SVI rank and percentage of uninsured individuals, (2) public health risks, measured by rates of COPD, asthma, and SDWA non-compliance, and (3) proximity to environmental hazards, specifically surface coal mines and hydrologic features.

Surface mine data from the Global Energy Monitor was filtered in Excel to isolate only surface mining operations in West Virginia. These filtered records were imported into ArcGIS Pro using the XY Table to Point tool and spatially joined to county shapefiles to calculate the number of surface mines per county. A new field, "mine density," was created by dividing the number of mines by each county's land area. The six counties with the highest mine density were extracted as a new shapefile to serve as an extent for the analysis. Mines outside of this area were excluded using an Intersect operation, and the Distance Accumulation tool was performed to generate a raster layer in which lower pixel values represent areas closer to mining activity. Each of the vulnerability and health indicators were extracted from Policy Map as a CSV file and joined to a U.S. Census tract shapefile using the GEOID identifier. These data were clipped to the six target counties and converted to raster format using the Polygon to Raster tool. Hydrologic features, including rivers, streams, and floodplains, were extracted from land use data using Raster Calculator. The Distance Accumulation tool was used again, this time generating a raster layer in which lower pixel values represent areas closer to hydrologic features.

Seven raster layers in total were included in the weighted analysis: The five vulnerability and public health indicative raster layers and the two representing proximities to hazards. The small transformation function was applied to the two distance raster layers, so that lower proximity values were assigned higher suitability scores (areas of higher risk). Linear transformations were applied to the five vulnerability and health raster layers so that higher values corresponded to higher suitability scores. Weights were then distributed among the three groups: proximity to hazards (50%), public health risks (25%), and social vulnerability (25%). Within the vulnerability and health risk groups, weights were distributed equally, resulting in 8.33% for each public health indicator and 12.5% for each vulnerability indicator. 32.5% was attributed to proximity to mines, leaving 17.5% to be attributed to proximity to hydrology. The proximity weights were derived based on a risk assessment of uranium mine contamination in a Navajo community (Lin et al., 2019). The remaining weights were derived based on an urban flood risk assessment in Kermanshah, Iran (Eini et al., 2020).

This configuration produced a composite raster identifying areas of highest cumulative environmental risk and lowest adaptive capacity within the six-county region of study. Areas lacking complete data for one or more indicators were excluded from the final risk surface and appear as gray zones in the output map (see **Figure 1**).

Results

The weighted risk analysis reveals a spatial pattern of vulnerability within the six most surface mine-dense counties in West Virginia. Areas with the highest cumulative risk score, indicated in red, are areas that are near surface coal mines and hydrologic features, exhibit high rates of respiratory disease, and have higher rankings of non-compliance with the Safe Drinking Water Act. Areas at most risk include central Wyoming County, southern Raleigh County, and eastern Mingo County. This reinforces the finding that environmental exposure and public health risks are geographically concentrated and not evenly distributed across all regions.

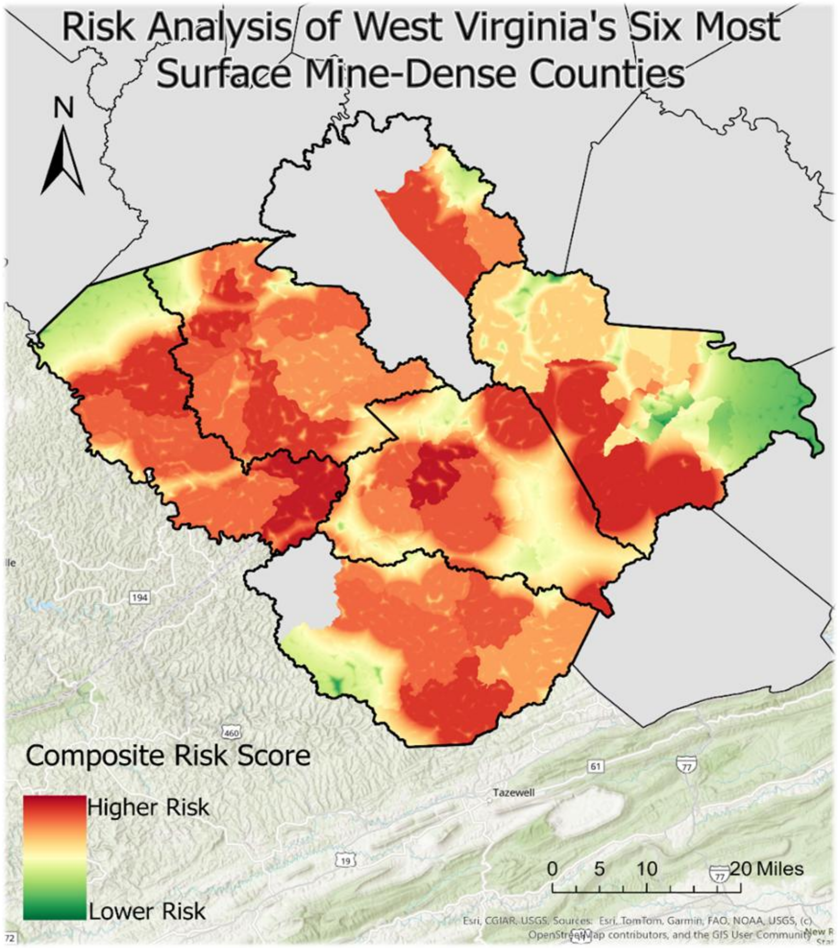

Figure 1. Map showing areas at most risk of adverse impacts from surface coal mining within the six most surface mine-dense counties of West Virginia.

This pattern also reflects the broader themes observed in the literature. Prior studies have shown how surface coal mining disproportionately impacts communities facing socioeconomic disadvantage. This analysis confirms that tracts with higher Social Vulnerability Index rankings and uninsured populations often coincide with areas of environmental risk. By integrating proximity data with public health and social indicators, this analysis not only supports existing findings, but provides a localized case study of where environmental and health stressors overlap. In doing so, it creates a stronger framework for identifying priority areas for mitigation, monitoring, or even restorative action.

The risk analysis sets up the second geospatial analysis to be performed in this area. The second analysis will be a weighted site suitability analysis determining where the ideal areas for restoration via reforesting in the six counties. This analysis will consider composite risk score, proximity to closed mines, slope, soil quality, and land cover when determining ideal locations. By including the risk assessment, the site suitability analysis will integrate both social benefits and environmental restoration, ensuring effective mitigation and restoration.

Site Suitability

This risk analysis sets up the second geospatial analysis to be performed in this area. The second analysis will be a weighted site suitability analysis determining where the ideal areas for restoration via reforesting in the six target counties. This portion of the analysis integrates the risk assessment results with topographic criteria that directly impact the reforestation potential of a given area. Specifically, slope, soil quality- measured through cation exchange capacity (CEC)- and land use were used to identify the most suitable areas. Five separate data elevation models (DEMs) were extracted from the USGS national map viewerto ensure complete elevation coverage across all six counties in the study area. Slope is a key factor, as it affects soil thickness, compaction, erosion, and water retention, all of which are critical for sustainable, resilient forest growth (Fan et al. 2024, 4). Soil CEC is equally important, as it determines a soil's ability to retain and supply the necessary nutrients for long-term forest recovery. Lastly, the land use raster was used to isolate areas heavily impacted by mining, aligning with the focus of this study.

Methodology

This analysis builds upon the risk assessment by identifying areas that meet the following criteria: they are abandoned mine sites- prioritizing surface coal mine barrens- have low slope for optimal tree planting, possess high CEC for optimal soil conditions, and are located in regions at highest risk of surface coal mining impacts. As preformed prior, each of the datasets were imported into ArcGIS Pro and projected to the NAD 1983 UTM Zone 17N coordinate system to ensure accuracy across layers. First, the mosaic tool was used on the five DEM models to create one continuous elevation layer. The slope function was then performed, yielding a raster layer depicting slope in degrees of the target area. Then, each raster was then masked by the risk analysis map, which included every section of the six target counties that had available data.

Next, because CEC values ranged from 5.2 to 24.6, the CEC data was normalized to a 0-1 scale to ensure consistency. The following formula was used in the raster calculator function to create the normalized raster, where C = CEC, min = 5.2, and max = 24.6:

$$\text{Normalized CEC} = \frac{C - min}{max - min}$$

This function yielded a raster layer with values from 0-1, higher values indicating better CEC. The CEC, slope, land use, and risk layers were integrated into a site suitability analysis using the Suitability Modeler in ArcGIS Pro. Transformations were applied based on methods adapted from a reforestation suitability study in Hebei Province, China: slope was transformed using the "range of classes" function, and land use was transformed using the "unique values" function (Fan et al. 2024, 6). The CEC and risk layers were transformed using the "large" function, which assigns higher suitability values to areas with higher CEC and higher risk.

Weighting values were initially derived from Fan et al. (2024), with adjustments made to account for the inclusion of a fourth criterion, the risk layer, and the exclusion of three criteria used in the original study. The original weights for slope, soil quality (CEC), and land use were 0.087, 0.1, and 0.354, respecitvely, totaling to 0.791. To integrate the additional risk layer, a default weight of 0.25 was assigned to risk. The four weights were then normalized by dividing each by 0.791, yielding the final weights used in this analysis, as shown in **Table 1**.

Transformation Type	Layer	Criteria / Classes	Suitability	Score	Weight
Unique Values	Land Use	Mine Barren	High	10	44.8%
		Mine Grass/ Shale Barren	Moderate	5	
		Other Barren Land	Marginal	3	
		Others	Unsuitable	1	
Range of Classes	Slope (°)	< 15°	High	10	11.0%
		15° – 25°	Moderate	5	
		25° – 35°	Marginal	3	
		> 35°	Unsuitable	1	
Continuous Function	Cation Exchange Capacity	Highest values → Most Suitable Lowest values → Least Suitable	—	10 ↓ 1	12.6%
Continuous Function	Risk Analysis Model	Highest values → Most Suitable Lowest values → Least Suitable	—	10 ↓ 1	31.6%

Table 1. Transformation methods and weights for suitability criteria.

The suitability model was calculated once the weights were applied, yielding a map depicting the most and least suitable areas for reforestation in green and red respectively. Once the model was completed, the locate function was used with the following parameters: a total search area of 80 km^2, 10 regions, an elliptical region shape, and individual region sizes ranging from 2 to 8 km^2. This yielded a new layer which depicted the ten most suitable locations outlined in black, as depicted in **Figure 2**.

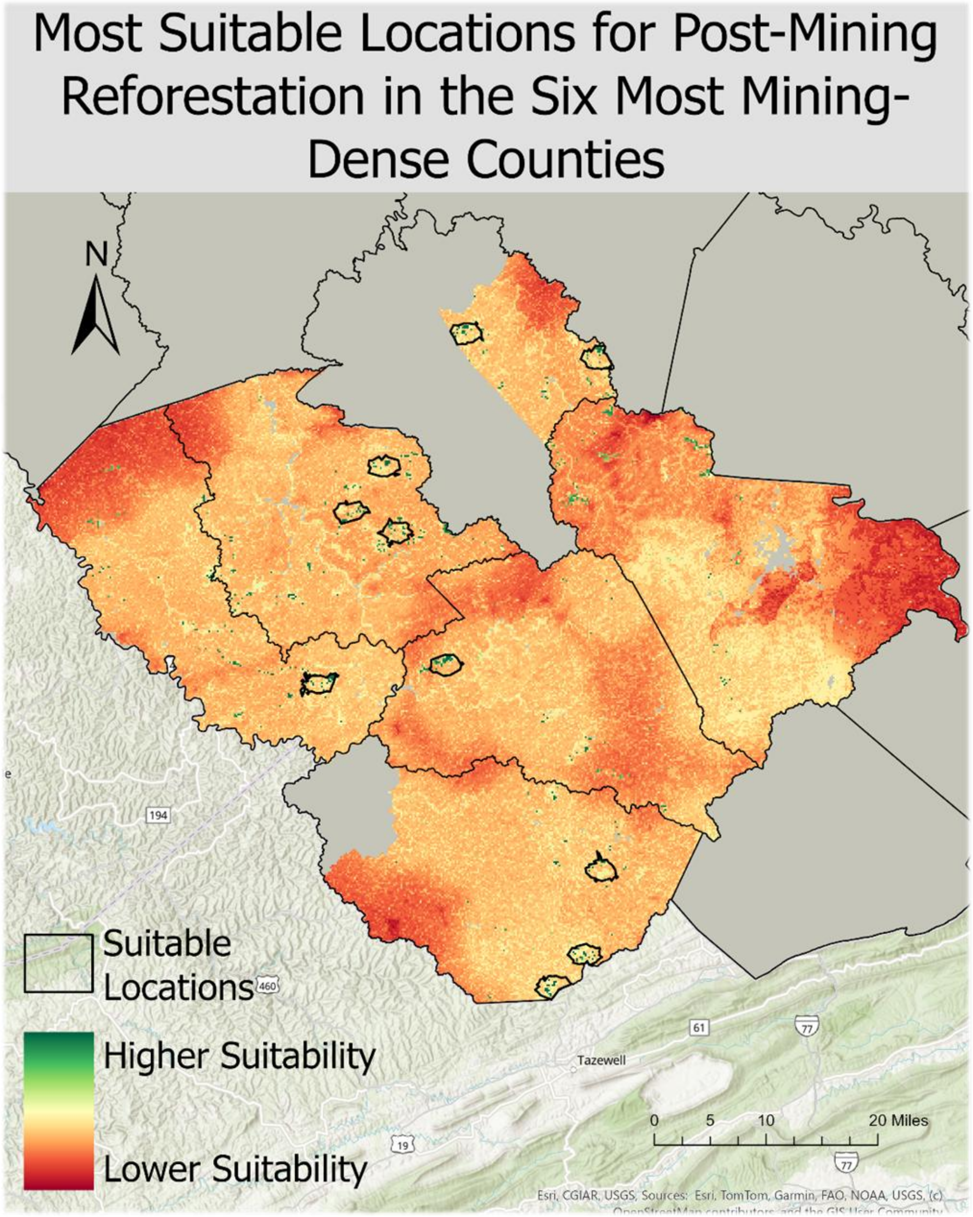

Figure 2. Map showing areas that are most suitable for restoration via reforestation, the ten most suitable areas outlined in black.

Results

The site suitability analysis identified a range of favorable areas for post-mining reforestation across the six target counties in West Virginia. The final suitability map illustrates these areas using a gradient from red (least suitable) to green (most suitable), with the ten optimal locations outlined in black. These areas reflect a balance of high-risk exposure, minimal slope, and strong soil fertility, all while being located on surface mine barrens. Notably, many of the most suitable regions were located near county borders, with high concentrations in Boone, Logan, and McDowell counties. These concentrations suggest that restoration efforts targeted in these areas could provide both environmental benefits and public health support to some of the region's most vulnerable communities. The results of the suitability analysis highlight how integrating topographic, soil, land use, and risk-based factors can guide more strategic restoration planning. By intersecting areas that fit the ecological criteria with areas high at risk, the model emphasizes the importance of socially conscious reforestation. This model also offers a replicable and adjustable framework for prioritizing post-mining restoration projects across Cental Appalachia as well as broader geographies, ensuring that future reclamation efforts maximize both environmental and community benefits.

Both the risk assessment and the site suitability models demonstrate the power GIS has to influence truly impactful restorative efforts. By combining a variety of social, topographic, and geographic indicators, these models offer a more comprehensive understanding of restoration planning that simultaneously prioritizes ecological function and community well-being. The results clearly identify both areas that are at highest risk, areas where intervention is needed, and ten starting areas for restorative efforts. While further refinement and the addition of more datasets could enhance future analyses, this study provides a solid model that is easily replicated and adaptable for guiding mitigation and restoration efforts elsewhere.

Conclusion

Proper mitigation and restoration efforts are needed in Central Appalachian communities, due to the legacy of environmental degradation and public health disparities caused by surface coal mining. This research has shown how mining-related topographic transformation and hydrologic contamination not only disrupts local ecosystems but exposes vulnerable communities to further health risks. By integrating spatial analysis into this conversation, this paper offers a clearer understanding of where these risks are most concentrated and how targeted restoration efforts could be applied most effectively. The risk assessment, which layered proximity to environmental hazards, public health risks, and vulnerability indicators, revealed hotspots where the need for intervention is most urgent. These findings both reinforce what previous literature has discussed about the unequal burden of coal mining and demonstrate how GIS can help inform more equitable and community driven restoration practices.

These findings emphasize the need for both expanded restoration efforts and continued geospatial analysis. While reforestation through the FRA remains widely practiced, its success is highly dependent on soil quality and site-specific conditions, which highlights the need for coupling it with strategies like soil reconstruction and wetland creation. As mining continues in parts of the region, more sustainable operational practices such as optimizing operational efficiency and implementing on-site water treatment systems can help reduce immediate effects. Future research should expand upon suitability modeling for restoration, incorporating more detailed environmental variables across broader geographies. Because the data used in this analysis are publicly available, the developed risk and site suitability models can be applied across all Central Appalachian counties. With appropriate regional adjustments, this framework could also be adapted for use in other mining-impacted areas beyond Appalachia.

Addressing the impacts of surface coal mining in Central Appalachia will require collaboration between researchers, policymakers, and local communities. This means the focus should be shifted from simply meeting reclamation standards to genuinely restoring ecological function and community well-being in the long term. Policymakers and researchers should treat spatial analyses not as end points, but as starting points for resource allocation, risk communication, restoration planning, and broader implementation. By centering restoration around both the environment and the people, Central Appalachia can move to become a safer, more sustainable region. Further research should continue refining spatial models by incorporating real-time environmental monitoring, longitudinal health data, and community input. Research can be further expanded as technology is improved, as more advanced operating machines can process and run larger and more complex datasets. With the right tools, data, and collaboration, Central Appalachia and other similarly affected regions can begin to restore damaged landscapes and work toward a healthier, more sustainable future.

Works Cited

Bernhardt, E. S., Lutz, B. D., King, R. S., Fay, J. P., Carter, C. E., Helton, A. M., Campagna, D., & Amos, J. (2012). How Many Mountains Can We Mine? Assessing the Regional Degradation of Central Appalachian Rivers by Surface Coal Mining. *Environmental Science & Technology*, *46*(15), 8115–8122. https://doi.org/10.1021/es301144q

Clark, E. V., Soucek, D. J., Schoenholtz, S. H., Whitmore, K. M., & Zipper, C. E. (2023). Trace Elements and Consequent Ecological Risks in Mining-Influenced Streams of Appalachia. *Environmental Toxicology and Chemistry*, *42*(12), 2651–2665. https://doi.org/10.1002/etc.5734

Cooper, D. B., Walker, C. J., & Christian, W. J. (2022). Maternal proximity to mountain-top removal mining and birth defects in Appalachian Kentucky, 1997–2003. *PLOS ONE*, *17*(8), e0272998. https://doi.org/10.1371/journal.pone.0272998

Eini, M., Kaboli, H. S., Rashidian, M., & Hedayat, H. (2020). Hazard and vulnerability in urban flood risk mapping: Machine learning techniques and considering the role of urban districts. *International Journal of Disaster Risk Reduction*, *50*, 101687. https://doi.org/10.1016/j.ijdrr.2020.101687

Fan, N., Wang, Y., Yang, X., Li, J., Kang, J., Liu, Q., & Zhang, Z. (2024). Suitability assessment for forest landscape restoration based on species diversity conservation. *Frontiers in Forests and Global Change*, *7*. https://doi.org/10.3389/ffgc.2024.1252077

Frigerio, I., Ventura, S., Strigaro, D., Mattavelli, M., De Amicis, M., Mugnano, S., & Boffi, M. (2016). A GIS-based approach to identify the spatial variability of social vulnerability to seismic hazard in Italy. *Applied Geography*, *74*, 12–22. https://doi.org/10.1016/j.apgeog.2016.06.014

Global Energy Monitor (2024). *Global Coal Mine Tracker - April 2024* [Data set]. https://globalenergymonitor.org/projects/global-coal-mine-tracker/download-data/

Hendryx, M., Zullig, K. J., & Luo, J. (2020). Impacts of Coal Use on Health. *Annual Review of Public Health*, *41*(Volume 41, 2020), 397–415. https://doi.org/10.1146/annurev-publhealth-040119-094104

Iepure, G., & Pop, A. (2025). Treatment of Acid Mine Water from the Breiner-Băiuț Area, Romania, Using Iron Scrap. *Water*, *17*(2), NA-NA. https://doi.org/10.3390/w17020225

International Soil Reference and Information Centre (2020). *Cation exchange capacity (at ph 7)* [Data set]. https://soilgrids.org/

Krometis, L.-A., Gohlke, J., Kolivras, K., Satterwhite, E., Marmagas, S. W., & Marr, L. C. (2017). Environmental health disparities in the Central Appalachian region of the United States. *Reviews on Environmental Health*, *32*(3), 253–266. https://doi.org/10.1515/reveh-2017-0012

Lin, Y., Hoover, J., Beene, D., Esther, E., & Zhuoming, L. (2020). Environmental risk mapping of potential abandoned uranium mine contamination on the Navajo Nation, USA, using a GIS-based multi-criteria decision analysis approach. *Environmental Science and Pollution Research*, *27*(24), 30542–30557. https://doi.org/10.1007/s11356-020-09257-3

Lindberg, T. T., Bernhardt, E. S., Bier, R., Helton, A. M., Merola, R. B., Vengosh, A., & Di Giulio, R. T. (2011). Cumulative impacts of mountaintop mining on an Appalachian watershed. *Proceedings of the National Academy of Sciences*, *108*(52), 20929–20934. https://doi.org/10.1073/pnas.1112381108

Naslund, L. C., Gerson, J. R., Brooks, A. C., Walters, D. M., & Bernhardt, E. S. (2020). Contaminant Subsidies to Riparian Food Webs in Appalachian Streams Impacted by Mountaintop Removal Coal Mining. *Environmental Science & Technology*, *54*(7), 3951–3959. https://doi.org/10.1021/acs.est.9b05907

Pericak, A. A., Thomas, C. J., Kroodsma, D. A., Wasson, M. F., Ross, M. R. V., Clinton, N. E., Campagna, D. J., Franklin, Y., Bernhardt, E. S., & Amos, J. F. (2018). Mapping the yearly extent of surface coal mining in Central Appalachia using Landsat and Google Earth Engine. *PLOS ONE*, *13*(7), e0197758. https://doi.org/10.1371/journal.pone.0197758

PolicyMap (n.d.). *Crude percent of chronic obstructive pulmonary disease among adults in 2022* (Tract) [Data set]. https://www-policymap-com.libproxy.temple.edu/newmaps/e/temple

PolicyMap (n.d.). *Crude percent of current asthma among adults in 2022* (Tract) [Data set]. https://www-policymap-com.libproxy.temple.edu/newmaps/e/temple

PolicyMap (n.d.). *Drinking Water Non-Compliance Supplemental Index (State Percentiles)* (Tract) [Data set]. https://www-policymap-com.libproxy.temple.edu/newmaps/e/temple

PolicyMap (n.d.). *Estimated percent of all people without health insurance, between 2019-2023* (Tract) [Data set]. https://www-policymap-com.libproxy.temple.edu/newmaps/e/temple

PolicyMap (n.d.). *Social vulnerabilty index (SVI) as of 2022* (Tract) [Data set]. https://www-policymap-com.libproxy.temple.edu/newmaps/e/temple

Rai, S. S., Murthy, V. M. S. R., Sukesh, N., Sairam Teja, A., & Raval, S. (2021). Operational efficiency of equipment system drives environmental and economic performance of surface coal mining—A sustainable development approach. *Sustainable Development*, *29*(1), 25–44. https://doi.org/10.1002/sd.2129

Ross, M. R. V., McGlynn, B. L., & Bernhardt, E. S. (2016). Deep Impact: Effects of Mountaintop Mining on Surface Topography, Bedrock Structure, and Downstream Waters. *Environmental Science & Technology*, *50*(4), 2064–2074. https://doi.org/10.1021/acs.est.5b04532

Ruktanonchai, C. W., McKnight, M. X., Buttling, L., Kolivras, K., Krometis, L.-A., & Gohlke, J. (2022). Identifying exposure pathways mediating adverse birth outcomes near active surface mines in Central Appalachia. *Environmental Epidemiology*, *6*(3), e208. https://doi.org/10.1097/EE9.0000000000000208

Sherman, L., Barton, C. D., Guzy, J. C., Davenport, R. N., Cox, J. J., Larkin, J. L., Fearer, T., Newman, J. C., & Price, S. J. (2024). Wetland Creation and Reforestation of Legacy Surface Mines in the Central Appalachian Region (USA): A Potential Climate-Adaptation Approach for Pond-Breeding Amphibians? *Water*, *16*(9), NA-NA. https://doi.org/10.3390/w16091202

Skousen, J. G., Dallaire, K., Scagline-Mellor, S., Monteleone, A., Wilson-Kokes, L., Joyce, J., Calene, T., Keene, T., DeLong, C., Cook, T., & Jacobs, D. F. (2018). Plantation performance of chestnut hybrids and progenitors on reclaimed Appalachian surface mines. *New Forests*, *49*(5), 599–611. https://doi.org/10.1007/s11056-018-9643-7

Thomas, C. J., Shriver, R. K., Nippgen, F., Hepler, M., & Ross, M. R. V. (2023). Mines to forests? Analyzing long-term recovery trends for surface coal mines in Central Appalachia. *Restoration Ecology*, *31*(5), e13827. https://doi.org/10.1111/rec.13827

U.S. Census Bureau (2024). *TIGER/Line Shapefiles: 2024 Census Tracts* [Data set]. https://www.census.gov/cgi-bin/geo/shapefiles/index.php?year=2024&layergroup=Census+Tracts

United States Geological Survey (2023). *USGS National Elevation Dataset (NED) 1/3 Arc Second* [Data set]. https://apps.nationalmap.gov/downloader/

West Virginia GIS Technical Center (2020). *WV Land Use Land Cover (NAIP 2016)* [Data set]. https://www.wvgis.wvu.edu/data/dataset.php?ID=489

Zipper, C. E., Adams, M. B., & Skousen, J. (2021). The Appalachian Coalfield in Historical Context. In C. E. Zipper & J. Skousen (Eds.), *Appalachia's Coal-Mined Landscapes* (pp. 1–26). Springer International Publishing. https://doi.org/10.1007/978-3-030-57780-3_1

Zipper, C. E., Burger, J. A., Barton, C. D., & Skousen, J. G. (2013). Rebuilding Soils on Mined Land for Native Forests in Appalachia. *Soil Science Society of America Journal*, *77*(2), 337–349. http://libproxy.temple.edu/login?url=https://www.proquest.com/scholarly-journals/rebuilding-soils-on-mined-land-native-forests/docview/1424345379/se-2

Zipper, C. E., Burger, J. A., McGrath, J. M., Rodrigue, J. A., & Holtzman, G. I. (2011). Forest Restoration Potentials of Coal-Mined Lands in the Eastern United States. *Journal of Environmental Quality*, *40*(5), 1567–1577. http://libproxy.temple.edu/login?url=https://www.proquest.com/scholarly-journals/forest-restoration-potentials-coal-mined-lands/docview/887765465/se-2