The uncertain future of mountaintop-removal-mined landscapes 1: How mining changes erosion processes and variables

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Graphical Abstract

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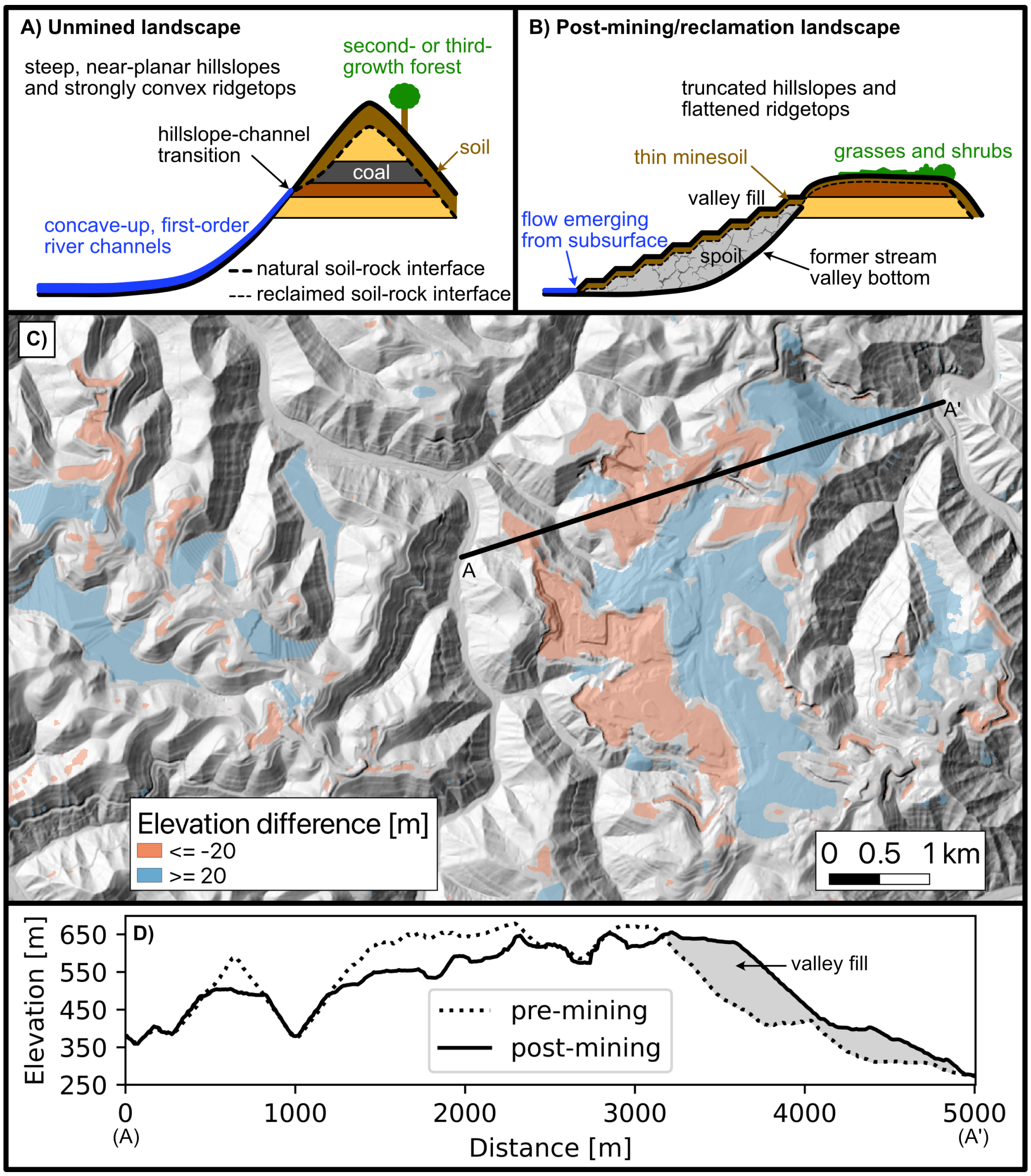

Highlights

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- Mountaintop removal mining flattens topography and moves drainage divides.
- Cut and filled domains generate different quantities of erosive runoff.
- Creation of many closed depressions reduces applicability of common models.
- Vegetation loss and material property changes increase erodibility.
- Our work reveals the necessary elements for models of post-mining landscape change.

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Abstract

Surface mining may be humanity's most tangible impact on Earth's surface, and will become more prevalent globally as the energy transition progresses. Prediction of post-mining landscape change can help mitigate environmental damage and allow effective reuse of mined lands, but requires understanding how mining changes geomorphic processes and variables. Here we investigate surface mining's complex influence on surface processes in a case study of mountaintop removal (MTR) coal mining in the Appalachian Coalfields, USA. The future evolution of MTR-influenced landscapes is unclear, largely because the ways that human changes to the landscape affect geomorphic processes are poorly understood. Here we use geospatial analysis—leveraging the existence of pre- and post-MTR elevation models—and synthesis of literature to ask how MTR alters topography, hydrology, and land-surface erodibility and how these changes could be incorporated into numerical models of post-MTR landscape evolution.

MTR mining reduces slope and slope–area product, and dramatically rearranges drainage divides. Creation of large numbers of closed depressions alters flow routing and casts doubt on the utility, especially over human timescales, of models that assume steady, uniform flow. MTR mining creates two contrasting hydrologic domains, one in which overland flow is generated efficiently due to a lack of infiltration capacity, and one in which waste rock

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deposits act as extensive subsurface reservoirs. This dichotomy creates localized hotspots of overland flow and erosion. Loss of forest cover probably reduces cohesion in near-surface soils for at least the timescale of vegetation recovery, while human-made VFs and mine soils also likely experience reduced erosion resistance. Our analysis suggests three necessary—though potentially not sufficient—ingredients for numerical modeling of post-MTR landscape change in the Appalachians: 1) accurate routing and accumulation of unsteady, nonuniform overland flow across low-gradient, engineered landscapes, 2) separation of the landscape into cut, filled, and unmined regions, and 3) incorporation of vegetation recovery trajectories. Our companion paper explores this final ingredient in detail. Improved modeling of post-mining landscapes will mitigate environmental degradation from past mining and reduce the impacts of future mining that supports the energy transition.

Keywords: Post-mining erosion, Landscape evolution, Appalachia, Reclamation, Erosion prediction

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1. Introduction

Earth's surface is a coupled natural–human system. Humans move more sediment than all natural surface processes combined (Hooke, 2000; Wilkinson, 2005). Predicting how landscapes will evolve into the future requires understanding how human modifications to Earth's surface influence geomorphic processes.

Large-scale surface mining is one of the most significant ways in which humans affect the shape, properties, and dynamics of Earth's surface. Order-of-magnitude estimates show that mining dominates the human-induced component of geomorphic activity across the contiguous United States (Hooke, 1994, 1999). The ongoing energy transition may drive further geomorphic impacts of surface mining due to increased demand for critical minerals (International Energy Agency, 2022; Shobe, 2022). Cascading environmental and human health effects of surface mining (e.g., Wickham et al., 2007; Palmer et al., 2010; Bernhardt and Palmer, 2011; Giam et al., 2018; Ross et al., 2021; Phillips, 2016; Patra et al., 2016; Fitzpatrick, 2018; Hendryx, 2015) make it essential to understand how mining affects geomorphic process dynamics, the trajectory of post-mining landscape evolution, and the relative merits of different reclamation strategies (e.g., Hancock, 2004; DePriest et al., 2015; Hopkinson et al., 2017).

Given the stakes, we are not well enough equipped to predict how Earth's surface evolves after mining disturbances. Studies related to surface mining have largely focused on hydrological (e.g., Ritter and Gardner, 1993; Negley and Eshleman, 2006; Miller and Zégre, 2014; Nippgen et al., 2017), biogeochemical (Ross et al., 2018; Brooks et al., 2019), and ecological (e.g., EPA, 2011; Wickham et al., 2007, 2013; Bernhardt et al., 2012; Giam et al., 2018) impacts. Those that focus on geomorphic impacts draw important conclusions about the structure and function of the post-mining landscape (e.g., Maxwell and Strager, 2013; Chen et al., 2015; Jaeger, 2015; Ross et al., 2016; Xiang et al., 2018; Feng et al., 2019; Reed and Kite, 2020; Jaeger and Ross, 2021; Joann and Allan, 2021), but do not clearly elucidate how mining will influence future landscape change.

A prolific body of work from Australian uranium mines on forecasting the erosion of individual mine-related landforms—waste rock dumps (Willgoose and Riley, 1998; Hancock et al., 2000), engineered hillslopes (Hancock, 2004), and tailings dams (Hancock, 2021; Hancock and Coulthard, 2022)—as well as single mine complexes (Hancock et al., 2008) and watersheds containing mine sites (Hancock et al., 2016) reveals the potential for astonishing complexity in how these landforms and landscapes erode after mining disturbances. When landscape properties like morphology (Lowry et al., 2019), surface grain size (Sharmeen and Willgoose, 2007), and vegetation (Evans and Willgoose, 2000; Hancock and Willgoose, 2021) are products of human choices rather than self-organization, the extent to which current landscape evolution theory (e.g., Barnhart et al., 2020a,b,c) might need to be modified to obtain predictive power becomes unclear.

Landscape alteration by large-scale surface mining therefore presents both an opportunity and a challenge for surface processes scientists. Mining gives rise to well-controlled "unnatural experiments" (cf. Tucker, 2009), or places where we can directly compare heavily modified landscapes to un- or lightly modified ones to elucidate how mining affects geomorphic processes and variables (e.g., Jaeger, 2015; Lowry et al., 2019; Jaeger and Ross, 2021). The challenge presented by surface mining is that it changes landscape form and process in ways not captured by our hard-earned understanding of natural geomorphic processes, creating landforms and process dynamics that would not exist without human intervention.

Perhaps the best example of surface-mining-driven landscape alteration can be found in the Appalachian Coalfields (AC) region of the eastern United States, where mountaintop removal (MTR) mining for coal has driven unique and dramatic changes to the land surface whose geomorphic impacts are not well understood. Here we seek to advance prediction of post-MTR landscape evolution—and the evolution of disturbed landscapes in general—by leveraging the unique unnatural experiment of MTR-modified landscapes to derive insight into human alterations to geomorphic processes and variables. We use geospatial analysis of pre- and post-MTR digital elevation models (DEMs), in conjunction with synthesis of existing literature, to assess the effects of MTR mining on three classes of erosion processes and variables: topography, hydrology, and surface erodibility. For each class of variables we seek to understand 1) how MTR alters the key variables within each class relative to minimally disturbed Appalachian landscapes, and 2) what the implications of these alterations are for modeling post-MTR landscape evolution. In our companion paper (Bower et al., in review), we quantify how mining-driven changes to topography and erodibility alter post-mining landscape evolution trajectories. Our goal is to provide a path forward for predicting future geomorphic change and resulting environmental hazards in these landscapes.

1.1. Geographic scope

Surface mining—broadly defined as blasting or scraping the Earth's surface down to reveal a deposit rather than digging a tunnel to access it—is practiced worldwide, spanning gradients in climate, ecology, lithology, and tectonics. While there are certainly similarities between surface-mined sites in different environments, there are also critical differences between regions in the processes and variables that drive geomorphic change. To better develop the ability to predict future land-surface change in mined regions, it is important to understand mining-induced changes to surface processes in the context of region-specific geologic, biologic, and climatic conditions as well as region-specific mining and reclamation practices.

The process of MTR and the landscape of Appalachia are inextricably intertwined, with many MTR mining procedures and mine reclamation regulations existing because of characteristics unique to the Appalachian landscape. Due to the unique topography and climate of the AC region, the specific features of AC coal deposits, and the peculiar American regulatory environment, Appalachian MTR mining creates land-surface changes that can differ in extent, significance, and style from those driven by other common surface mining practices (e.g., Willgoose and Riley, 1998; Duque et al., 2015).

We therefore focus on MTR mining in the AC region, which parallels the Appalachian orogen through Alabama, Tennessee, Kentucky, Virginia, West Virginia, Ohio, and Pennsylvania, USA. The bulk of MTR mining occurred, and continues to occurr, in West Virginia, Kentucky, and southwestern Virginia, where rugged topography and significant coal deposits coincide (Fig. 1). While some insights from the AC are likely limited in their relevance to other hotspots of surface mining (and vice versa) due to varying geologic and environmental conditions and mining practices, many mining-induced changes to AC landscape dynamics may shed light on post-mining landscape evolution in other regions (e.g., Hancock et al., 2000; Vidal-Macua et al., 2020; Shi et al., 2021).

2. Background: Mountaintop removal mining in the Appalachian Coalfields

2.1. The Appalachian Coalfields region

The AC region stretches from Alabama to Pennsylvania as part of the Appalachian Plateau physiographic province. The bulk of the AC region is made up of Pennsylvanian to early Permian (320–280 Ma) sedimentary rocks deposited in the Dunkard and Pocahontas Basins, which at the time were experiencing alternating shallow marine and fluvial depositional environments fed by sediments shed from the Appalachian Mountains (Eriksson and Daniels, 2021). The peat swamp environments common during this time enabled the formation of multiple, thick (up to >600 m; Eriksson and Daniels (2021)) coal beds.

While the stratigraphy of the AC remains relatively flat-lying due to a lack of significant post-deposition tectonic shortening in the region, the Appalachian Plateau and its near-surface coal deposits are now situated at significantly higher elevation (300–1200 m) than at the time of deposition. The causes of the Plateau's modern elevation remain unclear; the rise of the Plateau could have been caused by isostatic response to the excavation of valleys in the adjacent Valley and Ridge province (Anders et al., 2022; Spotila and Prince, 2022), or the Plateau may have experienced mantle-driven uplift in response to large-scale tectonic forcing (Flowers et al., 2012).

The forces driving the Plateau's elevation are not critical to our study, but the geomorphic response to that elevation is. The Plateau is composed of relatively flat-lying caprock (typically sandstone) into which deep, narrow river valleys are incised (Spotila and Prince, 2022). Early workers recognized the strong influence of rock properties on erosional forms in this landscape (e.g., Morisawa, 1962), and modern quantitative studies have confirmed that the Plateau that contains the AC region is best thought of as a relatively resistant surface undergoing relief production through fluvial incision (and hillslope response) that outpaces lowering of ridgetops (DiBiase et al., 2018; Gallen, 2018; Portenga et al., 2019). Cosmogenic nuclide erosion rates indicate that river-basin averaged erosion rates are 2–3 times faster than ridgetop outcrop lowering rates (Hancock and Kirwan, 2007; Portenga et al., 2019).

Such marked disequilibrium leads to a steep, highly erosive landscape where rivers are carving deep, narrow valleys into bedrock and most hillslopes are at or near their stability threshold (Figs. 1 and 2). The dominant natural geomorphic processes are soil production from bedrock by weathering, rapid downslope soil transport by debris flows, shallow landsliding, and/or rapid soil creep, and fluvial sediment transport and bedrock incision.

2.2. Mountaintop removal mining

While there have been a variety of methods used over time to mine coal in the AC (Skousen and Zipper, 2021), MTR mining has the most dramatic effects on the land surface. In MTR mining, miners use explosives and heavy excavating equipment to remove overburden from an entire ridge and access coal seams below. This approach takes advantage of the relatively shallow dip of coal seams in the AC to expose large quantities of coal at once. MTR yields enormous volumes of fractured waste rock, known as spoil or, somewhat confusingly, once it is laid down in a waste rock deposit, as overburden. Because previously intact rock is fractured during the mountaintop removal process, the volume of spoil can significantly exceed that of the previously intact mountaintop (Skousen and Zipper, 2021).

2.3. The post-mining landscape

The form and function of the post-MTR landscape in the AC region has since 1977 been dictated by the Surface Mining Control and Reclamation Act (SMCRA), intended to reduce negative long-term environmental consequences of mining by regulating reclamation practices. They key provision of SMCRA is that it requires mined lands to be returned to "approximate original contour," (AOC) which is defined as a landscape that "closely resembles the general surface configuration of the land prior to mining and blends into and complements the drainage pattern of the surrounding terrain." (quoted from SMCRA by Bell et al., 1989).

Returning landscape to AOC in the steep terrain of much of the AC region is not considered safe because it results in spoil piles shaped to resemble natural Appalachian hillslopes and mountaintops (Zipper et al., 1989), which are largely at or near the threshold for landsliding even when underlain by intact bedrock (e.g., Parker et al., 2016). Concerns about landsliding motivated a variance to SMCRA that allows reclamation of ridges without restoration to AOC and the storage of mine spoil in engineered valley fills (VFs) (Reed and Kite, 2020). The result is a landscape broadly partitioned into two anthropogenic domains, neither of which has a natural analog in the AC region.

MTR-mined ridges, or cut areas, are generally extremely low relief, standing out in DEMs as being the only flat portions of the AC region aside from river floodplains (Fig. 2). VFs are engineered deposits of mine spoil located in former headwater stream valleys. At depth VFs are composed of boulders generated by the fracturing and removal of waste rock during mining, with the interstitial area filled with smaller rock fragments and sand (Haering et al., 2004; Daniels et al., 2010; Greer et al., 2017; Reed and Kite, 2020). This mixture is compacted by heavy machinery in an effort to enhance slope stability (Schor and Gray, 2007). Soil, either stockpiled from before mining began, imported from elsewhere, or constructed from mine spoil itself (Daniels et al., 2010), is placed on the VF surface to encourage vegetation growth. VF slopes display a characteristic terraced shape (Maxwell et al., 2020) due to design regulations that dictate that they be composed of alternating segments of 2:1 (0.5 m/m) slope and near-zero slope (Fig 2). Mined ridges and VFs are typically planted with vegetation to fulfill a particular post-mining land use: farmland, hay/pasture, biofuel crops, forestry, unmanaged forest, wildlife habitat, or building site development (Skousen and Zipper, 2014, 2021). Achieving mature forest ecosystems on mined lands is largely aspirational, as forests do not seem to recover fully from mining disturbances (Ross et al., 2021; Thomas et al., 2022).

In addition to cut areas and VFs, mined landscapes host tailings piles and/or refuse impoundments consisting of coarse or fine coal refuse, waste material left over from mining (e.g., Salam et al., 2019). Geotechnical properties of refuse differ from those of bedrock, waste rock, and mine soil and may therefore evolve differently from other surfaces post-reclamation. Refuse impoundments are typically less areally extensive than cut ridges and VFs, but are portions of the landscape that may be exceptionally erosionally unstable due to the potential for the refuse to undergo liquefaction (Salam et al., 2020).

The practice of MTR was already widespread by 1977 (Bell et al., 1989), such that the AC region hosts a mix of mines that predate SMCRA reclamation regulations and those that postdate them. The composition and shape of VFs, for example, was standardized by SMCRA. While there are meaningful design difference between pre- and post-SMCRA reclamation efforts, the broad division of the post-mining landscape into cut and filled areas, both dotted with refuse impoundments, applies to both time periods.

2.4. Geomorphic controls on MTR's environmental impacts

Central Appalachia is a major biodiversity hotspot that hosts a variety of endangered species, including a number of species endemic to headwater streams (Bernhardt and Palmer, 2011, and refereces therein). MTR has major, well-understood environmental consequences for the region and its ecosystems (e.g., Palmer et al., 2010; EPA, 2011). The intensity and spatiotemporal distribution of many of MTR's negative environmental effects depend on geomorphic process dynamics. The efficiency of erosion on reclaimed mines controls sediment supply to nearby streams (Bonta, 2000) and determines the fluvial response to upstream mining (Jaeger, 2015). Erosion and sediment transport processes likewise influence the potential for successful ecologic restoration, as intense gully erosion or landsliding (Reed and Kite, 2020) can strip away the thin layer of soil that is typically returned to the surface during reclamation. Stream sediment may convey metals and arsenic downstream (Merricks et al., 2007), making sediment transport patterns an important control on the distribution of contaminants through aquatic ecosystems.

By abruptly redistributing millions of cubic meters of rock (Ross et al., 2016; Reed and Kite, 2020) in ways not possible through natural sediment transport processes, MTR mining sculpts a new landscape that differs from its pre-mining condition in myriad ways. In the following three sections we use geospatial analysis and synthesis of the literature to ask: How do mining-induced alterations to topography (section 3), hydrology (section 4), and land-surface erodibility (section 5), affect the shaping of mined drainage basins over landscape evolution timescales?

3. Alterations to topography

Topographic alteration is the clearest signature of MTR mining. Each MTR mining complex reshapes catchment hypsometry over horizontal scales of tens of kilometers and vertical scales of hundreds of meters (Figs. 2 and 3), all over years to decades. No natural process in the AC region can match MTR mining for sheer magnitude and rate of mass redistribution (Hooke, 1999). The distribution of elevation across landscapes sets the potential energy available to drive erosion both by flowing water and gravity-driven hillslope processes, making quantifying MTR-induced changes to topography critical for forecasting the evolution of mined lands.

3.1. Observed alterations

3.1.1. Elevation, slope, and drainage area

MTR mining flattens hilltops that previously exhibited steep slopes and strong negative curvature, and fills in low-order stream valleys (Figs. 2 and 3). This redistribution of mass has significant implications for basin hypsometry. Differencing pre- and post-mining DEMs in an 11,500 km^2 area within the AC region revealed that individual mined watersheds experience a narrowing of their elevation probability distribution (Ross et al., 2016; Jaeger and Ross, 2021), as previous topographic highs are demolished and topographic lows are filled with waste rock. Ross et al. (2016) and Jaeger and Ross (2021) demonstrated meaningful changes to the distribution of topographic slopes both in individual mined watersheds and in the study region as a whole: mining generates large areas with slopes near zero driven by the flattening of mountaintops, and a concomitant reduction in the amount of area that exhibits the region's average hillslope angle. The observation that mining altered slope distributions over the entire study area is particularly striking and speaks to the magnitude of the perturbation given that mining occurred on only slightly over 10% of the area.

One ecologically relevant way to view MTR-driven hypsometry changes is to classify pre- and post-mining landscapes into different landforms or geomorphons (e.g., summit, side slope, valley bottom, etc) using various digital terrain derivatives to infer topographic position (e.g., Maxwell and Strager, 2013; Maxwell and Shobe, 2022). Results of such analyses agree with mapped slope distributions: MTR mining drives losses in the relative proportion of steepland landforms and gains in the proportion of lower-slope landforms (Maxwell and Strager, 2013). Changes in landform distributions arise due to both the destructive (removal of mountaintops) and constructive (filling of headwater valleys) aspects of MTR mining.

Given the significant reorganization of the landscape's elevation structure, it is intuitive to expect changes to the effectiveness of different geomorphic processes (Jaeger and Ross, 2021). Because of the dramatic reduction in the proportion of the landscape underlain by steep slopes, the increase in areas of near-zero slope, and increases in the proportion of areas that have low drainage area (i.e., are located on summit flats where flow is not accumulated efficiently with distance), mined watersheds tend to have bimodal probability distributions of the product of slope and drainage area (AS)—a proxy for the potential for erosion by overland flow (e.g., Howard and Kerby, 1983). AS distributions in mined watersheds show a first peak near zero and a second peak that is lower and located at a lower slope–area value than in unmined watersheds (Jaeger and Ross, 2021). Mined basins exhibit the greatest reduction in slope at drainage areas typical of unchannelized or debris-flow-dominated valleys, which would under undisturbed conditions be the portions of the landscape sculpted by hillslope processes and debris flows (Jaeger and Ross, 2021). This reduction in slope could suggest reduced efficacy of low-drainage-area erosion processes in mined landscapes.

To further quantify the influence of mining's spatial extent on topography, we analyzed ratios of the post- to pre-mining distributions of elevation, slope, and area-slope product ($\sqrt{A}S$; we take the square root of A to acknowledge the relationships commonly observed in natural landscapes (e.g., Howard and Kerby, 1983; Whipple and Tucker, 1999)) among 88 Hydrologic Unit Code 12-digit (HUC-12) watersheds that overlap by at least 90% the pre- and post-mining DEMs of Ross et al. (2016). We explored the control of the percent of the watershed mined, using mined area data through 2015 from Pericak et al. (2018), over mean catchment morphology. We conducted Bayesian rank correlations (van Doorn et al., 2020) and consider a correlation robust if the 99% highest posterior density interval (HPDI) for the posterior distribution of the correlation coefficient (insets in Fig. 4) does not include zero.

We find significant correlations between the percent of the watershed mined and changes in mean elevation, slope, and area-slope product. The ratio of post- to pre-mining mean elevation is positively correlated with the percent of the watershed mined (Fig. 4A). This indicates that the filling of headwater valleys drives increases in elevation that outcompete reductions in elevation from mountaintop removal, likely due to the expansion of waste rock relative to its initial volume. The ratio of post- to pre-mining mean catchment slope is strongly, negatively correlated with the percent of the watershed mined (Fig. 4B); this could be partially attributed to the findings of Ross et al. (2016) and Jaeger and Ross (2021) that mined catchments exhibit large, flat areas that reduce the catchment-mean slope. However, we note that for 0–10% mining the post-mining mean slope exceeds the pre-mining slope, indicating that the construction of steep-faced VFs outweighs mountaintop removal as a control on mean slope at low proportions of catchment area mined. The ratio of slope–area product $\sqrt{A}S$ follows a similar pattern; it is strongly, negatively correlates with percent mined (Fig. 4C), supporting the idea that reductions in mean catchment slope reduce the mean erosive power of overland flow (Jaeger and Ross, 2021). But like the ratio of mean slopes, the ratio of $\sqrt{A}S$ only goes below a ratio of one at about 10-20% mined catchment area. Overall our results indicate strong control of mining over mean catchment statistics is clear, but the direction of the effect depends on how much of the watershed is mined.

We went beyond the means of elevation, slope, and slope–area product by analyzing the Wasserstein Distance (W_2; Lipp and Vermeesch (2022)) between the pre- and post-mining distribution of each quantity in each HUC-12 catchment. This is effectively a cost function that measures the relative difficulty of turning the pre-mining distribution of a quantity into the post-mining distribution. It is convenient because it does not require summarizing the distribution with a single number, and thus incorporates distribution shape information lost from our analysis of ratios of mean quantities.

Comparing W_2 between pre- and post-mining elevation, slope, and $\sqrt{A}S$ distributions as a function of percent mined for our 88 catchments tells a more complicated story. W_2 between pre- and most-mining elevation distributions strongly correlates with percent mined (Fig. 4D). Slope shows a correlation within the 95% HPDI but not the 99% HPDI, indicating a weaker correlation between percent mined and the distance between slope distributions (Fig. 4E). The posterior distribution of the correlation coefficient for W_2 for $\sqrt{A}S$ with percent mined is effectively symmetric about zero, meaning that there is no relationship between percent mined and the distance between pre- and post-mining distributions of $\sqrt{A}S$ (Fig. 4F). The Wasserstein distance between pre- and post-mining distributions of morphometric quantities might show less clear correlations with percent mined than the ratio of the means of those quantities because it measures only the magnitude, not the sign, of the difference between distributions. Therefore, the previously undocumented observation that both slope and $\sqrt{A}S$ both increase due to mining at low percent mined before decreasing at higher percent mined (Fig. 4A–C) explains why W_2 yields different results for these quantities than for elevation, which has—aside from noise—a floor at a post- to pre-mining ratio of one (Fig. 4A). Our results from 88 HUC-12 catchments indicate not only that mining rearranges catchment-scale topography as previously documented, but also that the extent and direction of that change depend heavily on how much of the watershed is mined.

Based on analysis of slope and slope–area patterns alone, the most intuitive prediction would be that, at least for catchments with a significant proportion of mined area, erosion processes are less efficient at all but the largest drainage areas because of landscape-wide reductions in slope. Field evidence suggests, however, that the potentially erosion-mitigating effects of mining-induced reductions in slope and drainage area may be outweighed by changes to hydrology and land-surface erodibility (Negley and Eshleman, 2006; Reed and Kite, 2020).

3.1.2. Drainage divide migration

MTR-induced modifications to elevation cause another important but previously underappreciated landscape change: the anthropogenic migration of drainage divides. Planview drainage divide migration is typically a process only observable over geologic time—except in rare instances of sudden drainage capture (e.g., Dahlquist et al., 2018)—driven by differences in cross-divide erosion rates (Whipple et al., 2017). By flattening the ridgetops that previously defined drainage basin boundaries, MTR can redistribute drainage area among basins over years to decades. The direction of divide migration caused by MTR depends only on the results of mining and reclamation processes instead of on the cross-divide erosion rate contrasts that dictate natural divide migration. By using TopoToolbox2 (Schwanghart and Scherler, 2014) to compare drainage basin configurations between pre-MTR and post-MTR DEMs together with remotely sensed mine location data (Pericak et al., 2018), we find that divides where mining occurs can shift by up to approximately 500 m over the 40-year period separating the two topographic datasets, yielding a time-averaged divide migration rate of over 10 m/yr (Figure 5). This is at least four to five orders of magnitude higher than typical divide migration rates in unmodified ancient postorogenic landscapes (Beeson et al., 2017).

3.2. Incorporating topographic alterations into models

Our work expands the catalog of mined landscape properties that can be thought of as "geomorphically incoherent" (Jaeger and Ross, 2021), an appropriate label emphasizing that mined watersheds do not fit into our paradigms because they are no longer self-formed. For example, while natural channel heads clustered tightly in slope–area space in an unmined Appalachian watershed, constructed channel heads in a nearby mined watershed spanned four orders of magnitude in drainage area, nearly two orders of magnitude in slope, and could not be defined by any one slope–area relationship (Jaeger and Ross, 2021). Despite the incoherence imposed by mining, we should be able to use process models derived from natural landscapes to estimate future MTR landscape change.

Landscape evolution models (LEMs) cast topographic change as some function of local slope, quantity of accumulated surface water, or both depending on the model and process domain under consideration (e.g., Willgoose et al., 1991; Tucker and Hancock, 2010). MTR-driven changes to basin hypsometry, slope distributions, and drainage area may have a profound influence on post-mining landscape change. Making matters easier is the fact that both slope and water quantity are typically derived directly from land-surface topography, which is treated as a state variable—sometimes the only one—in LEMs. Lidar-derived DEMs have revealed post-mining topography at high (1–3 m) resolution across the majority of the AC region; these DEMs can serve as initial conditions for modeling post-mining evolution of drainage basins. However, the rearrangement of topography due to MTR mining poses significant challenges for modeling due to the influence of topography on flow routing and basin hydrology.

4. Alterations to surface hydrology

Landscape surface hydrology governs the rates and spatiotemporal patterns of erosion by flowing water, thought to be the primary means of mass export from MTR-modified landscapes (e.g., Reed and Kite, 2020). We focus on surface water over groundwater dynamics because of its more direct connections to common landscape evolution modeling approaches, but acknowledge the importance and complexity of subsurface flow paths on MTR landscapes (e.g., Miller and Zégre, 2014; Nippgen et al., 2017). Dramatic reshaping of topography drives changes to the water balance and flow routing across mined areas. Many changes to land-surface hydrology arise from engineering choices (e.g., the composition of VFs and the locations of stormwater retention cells) that threaten to reduce the applicability of common LEM approaches.

4.1. Observed alterations

MTR mining affects overland flow dynamics by 1) changing the water balance of the landscape through altered rates of canopy interception, evapotranspiration, infiltration, and runoff generation and 2) changing flow routing through the reshaping of topography and the construction of drainage structures. These effects differ among sites due to variations in reclamation practices and the contrasts between mined ridge and VF landforms (Miller and Zégre, 2014), but in aggregate produce landscape hydrology that differs quantifiably from the pre-mining landscape and depends markedly on spatial scale. The post-mining land surface exhibits localized hotspots of overland flow (Negley and Eshleman, 2006) and erosion by gullying (Reed and Kite, 2020), while higher-order drainage basins tend to experience reductions in flood peaks and stormflow volumes (Nippgen et al., 2017). It is important to note that extreme heterogeneity in reclamation methods and materials across space and time means that the current body of work can only constrain general system tendency, not universal behavior (e.g. Phillips, 2004; Evans et al., 2015).

4.1.1. The water balance

Perturbations by MTR mining to vegetation and surface/subsurface material properties alter runoff generation in mined landscapes. Replacing mature forest with grasses and/or shrubs reduces canopy interception and evapotranspiration (Dickens et al., 1989; Ritter and Gardner, 1993; Miller and Zégre, 2014), leading to increased runoff generation for a given infiltration rate, while infiltration rates also change dramatically both between unmined and mined landscapes and between cut and fill areas within mined landscapes due to differences in subsurface structure (Figs. 3 and 6).

Reclaimed mines are surfaced with minesoil, a thin (several cm to tens of cm) mantle of either stockpiled pre-mining soil or imported topsoil overlying crushed waste rock or backfill (Bell et al., 1989; Guebert and Gardner, 2001; Skousen et al., 2021) and ultimately intact bedrock. In cut areas where topography has been removed to access coal, the bedrock may be covered by a layer of backfill but is generally close to the land surface as SMCRA does not require restoring steep hillslopes to their pre-mining shape. In fill areas, the land surface may be many tens of meters above the bedrock, with the intervening space filled with highly heterogeneous backfill (Fig. 3). These two spatial domains give rise to differing hydrologic responses to heavy precipitation events (Negley and Eshleman, 2006; Miller and Zégre, 2014; Nippgen et al., 2017): cut areas experience low infiltration rates and produce large volumes of surface runoff, while VFs tend to allow rapid infiltration and act as zones of subsurface water storage.

In the years immediately following reclamation, infiltration is often limited across both domains by compaction of restored minesoil (see review by Evans et al., 2015), though more modern reclamation guidelines call for limiting compaction to ameliorate this effect (Daniels et al., 2010). Infiltration rates in newly constructed minesoils tend to be lower than in undisturbed soils, but can in some cases recover within a few years to approximate infiltration rates in undisturbed soils (Jorgensen and Gardner, 1987; Guebert and Gardner, 1989; Ritter and Gardner, 1993; Guebert and Gardner, 2001). Increases in infiltration rate with time are not accompanied by changes in soil porosity, suggesting that infiltration rate increases in the post-reclamation years are driven by the development of near-surface macropores (Guebert and Gardner, 2001). These macropores develop in the minesoil but not the underlying backfill and their prevalence correlates with minesoil clay content (Guebert and Gardner, 2001). The mechanism that drives rapid recovery of infiltration rates post-reclamation is therefore thought to be clay shrink-swell, which develops an extensive macropore network in the minesoil and allows increasing infiltration as time elapses since reclamation.

In cases where minesoil infiltration rates recover to values observed in unmined landscapes, the local water balance subsequently depends on properties of the deeper subsurface (backfill and bedrock; Evans et al. (2015)). Backfill has more heterogeneous grain size distributions than most natural sediments, incoporating sand- to boulder-sized grains (Hawkins, 2004; Greer et al., 2017). In some cases, rapid infiltration of water through the minesoil layer—once macropore development has occurred—leads to throughflow along the minesoil-backfill interface (Guebert and Gardner, 2001), indicating that backfill can have lower hydraulic conductivity than recovered minesoils. However, fill material, because it is highly heterogeneous, has coarse-skewed grain size distributions, and lacks a significant clay fraction, often conveys water efficiently from the minesoil-backfill interface into the fill layer (Evans et al., 2015). In areas with deep layers of fill, like VFs, this allows storage of large volumes of water in the subsurface and reduced volumes of runoff generation relative to pre-mined Appalachian soils (Nippgen et al., 2017). In cut areas with only thin layers of fill between the bedrock and the minesoil, the fill layer cannot hold sufficient water to prevent rapid runoff generation (Haering et al., 2004; Negley and Eshleman, 2006).

The contrast between subsurface structure in cut and filled areas leads to a landscape with spatially variable runoff generation, where cut areas generate more runoff per unit rainfall than an unmined landscape would and filled areas generate less. This may explain, in part, Reed and Kite (2020)'s observation that gullies and other erosional landforms tend to be concentrated at the periphery of mine complexes, where cut surfaces generate runoff that then spills down steep adjacent hillslopes and drives erosion.

4.1.2. Flow routing

Mining-driven reshaping of surface topography and vegetation controls the accumulation of overland flow in space and time. The key first-order effects of mining—to flatten large portions of formerly steep land (Fig. 2–4) and replace mature forest with grasses and shrubs—have competing effects on spatiotemporal flow routing patterns. Reclaimed mine landscapes also typically include purpose-built features to influence the routing of potentially erosive runoff.

Disturbance of drainage divide locations by mining (Sec. 3; Fig. 5) occurs not only at the larger landscape scale but also at the scale of small, non-perennial catchments. Comparing flow accumulation maps derived from DEMs of pre- and post-mining landscapes (Fig. 7) demonstrates the extent to which MTR has reallocated water among first-order drainage basins. This hyperlocal drainage reorganization means that some catchments may become water-starved relative to their pre-mining condition, while some basins capture more rainfall than they previously did. When basins receive more water than they are geomorphically adjusted to convey, overland flow volumes are likely to exceed levels required to initiate detachment and transport of sediment, leading to mining-driven erosion hotspots (Reed and Kite, 2020; Jaeger and Ross, 2021).

The flattening of large portions of headwater catchments also affects the timing of runoff accumulation. Though cut areas produce overland flow efficiently for a given rainfall volume due to their lack of subsurface permeability, they also tend to be the flattest areas of the post-mining landscape (Fig. 3). The effects of slope reduction on flow routing are two fold: lower-sloping landscape patches tend to route flow to a larger number of downslope neighbors thereby inhibiting flow convergence and accumulation (Rieke-Zapp and Nearing, 2005), and water is transmitted downslope more slowly as overland flow velocity is sensitive to slope (e.g., Emmett, 1970). The flattened mountaintops in MTR landscapes may therefore, when considering topographic form alone, act to inhibit the formation of erosive pulses of overland flow by spreading out flow both spatially and temporally.

Reclamation engineers attmpt to shape post-mining topography in ways that reduce the volume and velocity of overland flow. Post-SMCRA reclamation typically includes the construction of retention cells, small closed depressions along the perimeter of mined areas intended to slow and broaden storm hydrograph peaks (see Fig. 2 in Reed and Kite, 2020). The stairstep design of VF faces is likewise prescribed in an effort to reduce volumes and velocities of overland flow. While the long-term effectiveness of these structures at reducing erosion is suspect (Reed and Kite, 2020), their presence does alter flow routing dynamics in post-mining landscapes.

The change in vegetation from mature forest to planted grass, shrubs, and/or immature forest likely also influences overland flow velocities and the rate of downslope flow accumulation. For grasses and shrubs, vegetation surface roughness is a good proxy for reduction in overland flow velocity (Bond et al., 2020), though grasses can be bent down under turbulent flows and therefore don't always add meaningfully to landscape surface roughness (Abrahams et al., 1994). It is probable that post-mining grass, shrub, or tree plantings provide less flow resistance than previous mature forest ecosystems and thereby allow for more rapid accumulation of erosive overland flow, though this has not to our knowledge been specifically tested on reclaimed mines in the AC region.

4.1.3. Combined effects of changes to water balance and flow routing

MTR-induced changes to landscape hydrology are complex, with past studies differing as to whether alterations to the water balance and flow routing cause the landscape to tend on average toward a regime of higher or lower flood peaks (e.g., Miller and Zégre, 2014; Evans et al., 2015). Does the lack of infiltration capacity and vegetation in cut areas of the landscape outcompete its typically low slopes to cause a net increase in overland flow peaks relative to unmined landscapes? Or does the presence of large, highly permeable VFs absorb sufficient precipitation to reduce overland flow discharge peaks below what they would be in an unmined region? Results from field and modeling studies suggest that the answer depends on the relative proportion of each type of mine landform and the spatial scale of interest.

In mined areas without VFs, increased overland flow due to surface compaction drives hydrograph peaks higher than in unmined basins (Negley and Eshleman, 2006). There is a limit to how spatially extensive such a "cut-only" landscape can be; overburden removed at the surface must go somewhere, and in SMCRA-conforming mines it typically is sculpted into VFs. The most comprehensive field study to date of combined MTR/VF landscapes (Nippgen et al., 2017) suggests that at the scale of perennial stream basins, the hydrologic storage capacity of VFs combines with the low slopes of cut areas to outcompete reductions in ET and infiltration rates and drive increased baseflow with reduced storm peaks.

From a post-reclamation erosion perspective, the dominance of baseflow in perennial streams likely reduces the amount of time streams exceed their sediment transport thresholds. However, the dramatic hydrologic differences between cut, filled, and unmined portions of the landscape can lead to local hotspots of erosion. Rapid erosion is expected whenever high volumes of overland flow coincide spatially with steep areas of the landscape; for example where cut areas give way to steep, unmined hillslopes (e.g., Reed and Kite, 2020; Jaeger and Ross, 2021). Localized hotspots of upland erosion combined with reduced transport threshold exceedance in mainstem channels might lead to fluvial sedimentation (Wiley, 2001; Jaeger, 2015). Spatiotemporal heterogeneity in erosion potential driven by complexities in land-surface hydrology raises the important question of how models for post-mining landscape evolution can include such variability.

4.2. Incorporating hydrologic alterations into models

An array of possibilities of varying complexity exists for how to treat the generation and movement of overland flow when modeling post-mining landscape change. In our companion paper (Bower et al., in review) we present the simplest possible case, that in which runoff is generated equally across the landscape and accumulates purely in proportion to upstream drainage area, as a starting point and basis for comparison. This approach incorporates changes to overland flow accumulation that arise from restructuring of topography (e.g., changes in the location of drainage divides, the creation or destruction of drainage basins, and human-made features like retention cells) because it accumulates flow based on the post-mining DEM that serves as an initial condition for topographic evolution. It does not, however, incorporate the effects on the water balance of differing surface and subsurface properties (i.e., cut versus fill areas). Because such simple LEMs contain the implicit assumption of steady, uniform overland flow, our initial effort also does not include the effects on the velocity of overland flow of changes to topographic slope (i.e., flattened mountaintops) or the presence of closed depressions that cause flow deceleration and ponding.

Modeling land-surface hydrology presents opportunities for near-infinite model complexity. We focus on three key first-order changes to land-surface hydrology that, given results from past studies and the modeling results in our companion paper (Bower et al., in review), are likely important to forecasting erosion of reclaimed Appalachian mine complexes. We suggest that there is sufficient uncertainty around other aspects of reclaimed mines, ranging from the presence of older, underground mines (Miller and Zégre, 2016) to the variation in VF subsurface properties (Haering et al., 2004; Evans et al., 2015), that additional model complexity is unwarranted at this time.

The chief opportunity for improving models of post-mining evolution of AC drainage basins beyond the initial foray in our companion paper (Bower et al., in review) is incorporating the distinction between cut, filled, and unmined regions (Figs. 3 and 6). Cut areas efficiently generate runoff compared to unmined and filled areas. They do so most dramatically for the first few years following reclamation (Ritter and Gardner, 1993; Guebert and Gardner, 2001), but this effect persists over at least the decadal timescales for which we have measurements (Negley and Eshleman, 2006) due to the close proximity of unweathered bedrock to the land surface (Fig. 6). VFs efficiently absorb rainfall and overland flow, and act as reservoirs that increase baseflow and reduce stormflow in mined drainages (Nippgen et al., 2017). The simplest way to incorporate these distinctions into an LEM is to set unique infiltration rates for each domain such that runoff generation varies among cut, filled, and unmined areas. Given the heterogeneity in post-mining landscapes (Phillips, 2004; Evans et al., 2015; Miller and Zégre, 2016) we cannot expect to parameterize infiltration dynamics in any more detailed way.

Forecasts of post-mining landscape change would also benefit from accounting for the attenuating effects of altered topography on peak flood volumes and erosive stresses. Flattening of previously steep hillslopes (Fig. 2, 4), together with the creation of closed depressions (Figs. 7 and 8) and purpose-built features like retention cells, can reduce flood peaks to the extent that these effects are not outcompeted by greater runoff generation from cut areas. One solution is to simulate overland flow dynamics directly, for example by coupling hydrodynamic models to LEMs (Coulthard et al., 2013; Adams et al., 2017a; Davy et al., 2017; Hancock and Coulthard, 2022). Moving beyond the restrictive assumption of steady uniform flow may enable testing of field-based hypotheses that seek to explain the causes of post-mining erosion hotspots (Reed and Kite, 2020; Jaeger and Ross, 2021).

Reclaimed mines are revegetated for a variety of land uses (Skousen and Zipper, 2014, 2021). Even those mines revegetated with a view towards restoring forests typically do not recover to their pre-mined condition (Ross et al., 2021; Thomas et al., 2022). Given the differences in evapotranspiration rates among pasture, post-mining forests, and unmined forests, as well as the differences in land-surface roughness that affect overland flow velocities, differentiating among spatially varying vegetation communities may improve post-mining erosion modeling outcomes. For example, we show in our companion paper (Bower et al., in review) that even when simulating post-mining erosion over 10 kyr timescales, significant proportions of mass export from the landscape occur during the post-reclamation vegetation regrowth period. If the assumption that vegetation exerts a meaningful control on overland flow dynamics and erosion is correct, the vegetation recovery trajectory on reclaimed mines may play an outsized role in determining the geomorphic future of mined lands.

The extent to which models of post-mining landscape change in MTR/VF landscapes need to acknowledge the observed complexity in land-surface hydrology varies with the timescale and goals of the analysis. We suggest that the most important element of mining-induced complexity is the difference in infiltration dynamics between cut, filled, and unmined areas. If additional model complexity is acceptable, simulation of unsteady, nonuniform flow can incorporate the effects of topographic reorganization on stormflow peaks, potentially helping to identify otherwise overlooked erosion hotspots. Over human timescales relevant to land management, differentiating spatially between different vegetation cover regimes may further enable accurate prediction of landscape change.

5. Alterations to land-surface erodibility

MTR mining affects not only the gravitational and fluid stresses that drive landscape change, but also the landscape's erodibility or susceptibility to those stresses. Rock and sediment properties, including physical and chemical properties both inherent to the material and imposed by vegetation communities, set the erodibility of the land surface. MTR mining is by its very nature a process of altering surface and subsurface material properties: overburden is blasted and crushed into waste rock, soil is moved or created and subsequently compacted, minerals from deep underground are exposed at the surface. These changes to physical and chemical substrate properties affect vegetation re-growth, which then feeds back to influence material properties. Understanding how mining alters land-surface erodibility is essential to modeling post-MTR landscape evolution.

5.1. Observed alterations

Mining and reclamation change the bulk properties of surface and near-surface material. Minesoils are typically composed of heavily compacted soils that may differ—both from natural Appalachian soils and from one another—in texture, bulk density, and hydrological, chemical, and biological properties (Feng et al., 2019; Greer et al., 2017). Minesoils vary greatly from site to site, but typically have an increased coarse grain size fraction (Bussler et al., 1984), a finer overall grain size distribution (Wali, 1999), increased pH and higher salinity (Zipper et al., 2013), reduced nitrogen, phosphorus, and other nutrients vital for vegetation (Shrestha and Lal, 2010; Zipper et al., 2013), and increased spatial heterogeneity of soil properties (Topp et al., 2010). At some sites compaction drives increased bulk density relative to natural soils (Shrestha and Lal, 2008), while at some sites this effect is outcompeted by the presence of coarse rock fragments that preserve large pore spaces.

Grain size alterations in post-mining landscapes are complex and may have competing effects. While VFs tend to be enriched in coarse fragments, they typically have a finer grain size distribution overall due to the addition of crushed fine-grained minesoils at the surface (Wali, 1999; Feng et al., 2019). Finer grains, in conjunction with a decrease in cohesion, could lead to enhanced erosion and gullying as the threshold of motion is decreased during runoff events (Reed and Kite, 2020). However, coarse fragments at the surface can reduce overland flow volumes by enhancing deep percolation of water (Asghari et al., 2011), and can reduce erosion due to overland flow by armoring the surface and increasing surface roughness (e.g., Bunte and Poesen, 1993; Shobe et al., 2021). An abundance of coarse fragments may also inhibit seed germination and allow water and nutrients to infiltrate below the rooting depth, affecting vegetation growth (Bussler et al., 1984; Zipper et al., 2013). While grain size likely changes slowly over time, some studies have found a decrease in the coarse fraction after a few years of reclamation and weathering processes (Mukhopadhyay et al., 2016). After many decades, minesoils may in some cases return to a texture similar to that of native soils (Johnson and Skousen, 1995).

Heavy compaction accomplished with large machinery in an effort to reduce erosion post-mining can substantially increase bulk density (Shrestha and Lal, 2008), decreasing soil aeration, permeability, and pore structure development. This increase in bulk density due to compaction can persist for decades before it declines back to levels most suitable for vegetation growth (Wang et al., 2016). Further, differential compaction leads to an increase in heterogeneity in the soil, complicating internal drainage and predictions of compaction effects on geomorphic processes (Haering et al., 2004; Feng et al., 2019). While compaction aims to decrease the erodibility of the landscape, it can also stymie infiltration and vegetation growth, potentially enhancing erosion.

Because of the inhospitable growing conditions found in reclaimed minesoils, vegetation cover, type, greenness, and overall diversity rarely return to pre-mining conditions even over multidecadal timescales (Latifovic et al., 2005; Franklin et al., 2012; Sena et al., 2021; Oliphant et al., 2017; Ross et al., 2021). A recent remote sensing study of long-term post-MTR vegetation recovery over 30 years in Central Appalachia found that only about 8% of post-mined sites recover to 95% of the original condition for a variety of vegetation indices (Thomas et al., 2022). The "arrested succession" phenomenon during forest regrowth on mined sites arises from changes in soil properties that prevent vegetation growth, which in turn reduces the rate at which vegetation helps soils return closer to their pre-mined state (Thomas et al., 2022; Sena et al., 2021; Franklin et al., 2012; Adams et al., 2017b).

The post-mining revegetation trajectory and its influence on erodibility vary depending on the choice of vegetation during reclamation, which is a function of the intended post-mining land use (Skousen and Zipper, 2014). After compaction of minesoils, restoration efforts often include planting of grasses to rapidly stabilize the bare ground (Skousen and Zipper, 2021; Sena et al., 2021). However, these ground cover plants can compete with tree seedlings for moisture and sunlight, leading to an inhibition of tree growth and development of a mature forest (Sena et al., 2021). Recent efforts to prioritize forest development, known as the "Forest Reclamation Approach" (FRA), have shown promise in improving post-mining reforestation (Burger et al., 2018; Zipper et al., 2011). However, the efficacy of FRA is unclear;

while some remote sensing proxies for vegetation health show improvement, others do not (Thomas et al., 2022). Even if restored sites attain a similar biomass to unmined sites, they tend to exhibit lower species diversity and an increase in invasive species (Sena et al., 2021; Wickham et al., 2013). Overall, complex dynamics between different plant functional types and material properties of soil determine the capacity for forest regrowth.

Though there is little theory to quantitatively connect post-MTR soil and vegetation properties with land-surface erodibility, mined lands probably experience an increase in erodibility relative to their unmined state due to finer surface grain sizes, reduced soil cohesion, and loss of mature vegetation. Erodibility likely declines over multidecadal timescales as vegetation growth adds cohesion and helps soils return some way towards their natural textures. It is unlikely however that mined land erodibility recovers to the pre-mining state over timescales less than the many millenia required for full development of a new soil profile.

5.2. Incorporating erodibility alterations into models

While the properties that set minesoil erodibility—bulk density, grain size, and vegetation-induced cohesion—are typically not explicitly included in LEMs (for exceptions of varying complexity see Temme and Vanwalleghem, 2016; Welivitiya et al., 2021), their effects may be incorporated by altering parameters that govern runoff flow conditions, sediment entrainment thresholds, hillslope sediment transport efficiency, and fluvial erodibility. Physical material properties can often be straightforward to include in models at least heuristically; in some cases there exist well-defined functional relationships between measurable physical properties and model parameters. For example, grain size alters the threshold for sediment entrainment in rivers (e.g., Shields, 1936) in ways that, while subject to environmental noise, are broadly understood. Cohesion alters slope stability and is generally thought to slow soil transport (Dietrich et al., 2001), so a lack of cohesion in minesoils relative to natural soils might be incorporated as a higher hillslope transport efficiency.

Incorporating vegetation into models is not as straightforward. Modeling the influence of vegetation on geomorphic processes requires an understanding of both geomorphic and ecological dynamics as well as feedbacks between the two (Osterkamp et al., 2012). Over shorter (annual to centennial) timescales, plants stabilize soils, adding effective cohesion and decreasing erosion rates due to root strength (Schmidt et al., 2001; Simon and Collison, 2002; Collins et al., 2004). However, the role of plants on erosional processes over long timescales (kyrs) is unclear; for example, sediment transport that occurs due to tree throw can account for a substantial proportion of sediment flux on hillslopes (Doane et al., 2021; Gabet and Mudd, 2010; Marston, 2010).

Vegetation effects can be incorporated into models for post-MTR landscape change in a bewildering array of ways: increases in the threshold stress for sediment entrainment by overland flow (e.g., Collins et al., 2004; Rengers et al., 2016); increases in soil cohesion and therefore stability of slopes (Schmidt et al., 2001; Simon and Collison, 2002); increases in land-surface roughness, infiltration, and interception of rainwater, reductions in the discharge, velocity, and erosive power of overland flow (Evans and Willgoose, 2000; Marston, 2010; Istanbulluoglu and Bras, 2005); and/or more generic decreases in land-surface erodibility (Evans and Willgoose, 2000; Istanbulluoglu and Bras, 2005; Sears et al., 2020; Bower et al., in review). At spatiotemporal scales directly relevant to post-mining land management, the presence of plants—while inhibiting erosion on average—can cause microtopography and roughness that might enhance the formation of rills and gullies (Marston, 2010), but this effect is likely second order relative to the general reduction in land-surface erodibility that vegetation provides and is not an essential ingredient in models of post-MTR landscapes. On average, over the sub-millennial timescales for which MTR reclamation plans are intended, vegetation can be modeled as reducing the erodibility of the post-mine landscape. It is probable, though not certain, that full restoration to mature forest ecosystems would progressively reduce erodibility over time.

We propose a simple qualitative framework for modeling the combined influences of changes to vegetation and material properties on land-surface erodibility (Fig. 9). The pre-mining landscape starts with some baseline erodibility set by the geologic, environmental, and to some extent land-use history of the AC region. Mining then drives an initial, dramatic increase in erodibility to some maximum post-reclamation value (while erodibility is likely even higher during active mining, we ignore that time period here). If reclamation practices are successful, erodibility should decline over time as vegetation takes hold and succession occurs. We might expect this decline in erodibility to be exponential-like if erodibility correlates to the maturity of the ecosystem, as that reflects the rough recovery trajectory of forests on MTR lands (Ross et al., 2021; Thomas et al., 2022). The long-term asymptote of the erodibility recovery function is set by 1) the maximum extent to which post-mining vegetation communities can return to their pre-mined state (e.g., Thomas et al., 2022) and 2) changes to material properties (grain size, cohesion, bulk density, etc) that might set the minimum erodibility reachable by a post-MTR landscape whose ecological community has fully recovered, if indeed that is possible. The long-term erodibility of the post-reclamation landscape if vegetation fully recovers could be greater than (Fig. 9A), equal to (Fig. 9B), or less than (Fig. 9C) the pre-mining erodibility. Intuition based on short-term studies of post-mining landforms (e.g., Reed and Kite, 2020; Jaeger and Ross, 2021) suggests that a long-term increase in erodibility is the most likely outcome, but it is not certain that this would always be the case.

MTR reclamation regulations are not intended to apply to landscape evolution ($> 10^4$ year) timescales, but the long-term interplay between vegetation and landscape dynamics is worth considering as mined landscapes will certainly be eroding long into the future. Complex feedbacks between vegetation and erosional processes preclude a simple prediction as to whether vegetation enhances or decreases erosion over the long term (Marston, 2010). In an LEM that includes plant growth and death along with vegetation-induced alterations to the sediment entrainment threshold, plants inhibit erosion on average but in so doing steepen the landscape, making erosive events more extreme when they occur (Collins et al., 2004). Vegetation may also alter the dominant erosional mechanisms in a landscape. Incorporating plants into an LEM by allowing vegetation to slow hillslope sediment transport efficiency, and to grow and die according to local erosion rates, reveals that while a bare landscape may be dominated by runoff erosion, dense vegetation may ultimately drive landslide erosion to dominate (Istanbulluoglu and Bras, 2005). At these timescales, we also expect variations in vegetation and landscape dynamics due to climatic changes (Werner et al., 2018; Schmid et al., 2018; Sharma et al., 2021; Sharma and Ehlers, 2022).

The complexity of interactions between material properties and vegetation highlights outstanding challenges that need to be addressed in order to accurately predict post-MTR landscape evolution. For example, while cohesion is traditionally thought to act as a yield stress for soil on hillslopes, recent work has shown that it alters fluvial sediment entrainnment thresholds (Sharma et al., 2022) and can even potentially lead to hillslope instabilities that cause soil to move faster (Glade et al., 2021). Another open-ended question is the role of grain shape, which can alter the rate and style of sediment transport Cassel et al. (2021); Cunez et al. (2023). This may be exceptionally important due to the production of fragments during the MTR mining process. In addition to improving our understanding of the role of specific material properties, substantial increases in heterogeneity of material properties such as grain size, shape, cohesion, and bulk density at MTR sites (Topp et al., 2010; Feng et al., 2019) call for the need to better incorporate heterogeneity into LEMs. Even the role of grain size, which has been thoroughly studied as a key control on sediment transport for decades, remains elusive when substantial heterogeneity is present (e.g., Hancock et al., 2020), especially in mixed human-natural systems like MTR mines that lack long term sorting processes to narrow grain size distributions.

Improving our understanding of properties like cohesion and grain shape will allow for better predictive models. Targeted fieldwork, especially at mined vs. unmined sites, could better constrain 1) how these properties change due to mining and 2) how this affects processes such as overland flow, gullying, and soil creep. For example, geotechnical testing (Russell, 2012) could determine how cohesion changes between sites due to changes in vegetation and other soil properties. Controlled laboratory experiments may also illuminate the role of material properties, which are challenging to isolate in the field.

Unlike for topographic and hydrologic alterations, there do not exist ready-made solutions beyond basic empiricisms for incorporating MTR vegetation and material property disturbances into models of subsequent landscape change. The success of post-MTR land management and hazard reduction depends on better quantifying the variables and processes that govern mined land erodibility.

6. Conclusions

Geospatial analysis comparing Appalachian landscapes before and after mountaintop removal mining, combined with synthesis of the literature, reveals key ways in which MTR mining changes geomorphic processes and illumnates three probably necessary ingredients for models of post-MTR landscape change—aside from topographic changes (Sec. 3), which are indeed striking but do not need to be treated explicitly given that topography is a state variable.

First, models need the ability to route unsteady, nonuniform flow across low-gradient landscapes where diverging flow and closed depressions are common (e.g., Coulthard et al., 2013; Adams et al., 2017a; Davy et al., 2017).

Second, the separation of the landscape into cut, filled, and unmined areas likely requires three separate treatments of the water balance: a high runoff, low runoff, and moderate runoff zone, respectively. Though there is much more complexity in MTR landscapes, we suggest the three-domain approach as a starting point that might bring more insight than assumptions of uniform water balance, but not require extensive subsurface information given that cut/filled/unmined can be obtained from simple DEM differencing (Maxwell and Strager, 2013; Ross et al., 2016). Third, observations from mined lands and general geomorphic theory suggest that to the extent that vegetation recovers on post-MTR landscapes, erodibility should decline in tandem. We hesitate to suggest a functional form for this relationship, except to say that an exponential decline in erodibility with time is suggested by remotely sensed vegetation recovery trajectories (Ross et al., 2021; Thomas et al., 2022) and might therefore represent a reasonable starting point. Our companion paper (Bower et al., in review) explores this approach.

Earth's surface is shaped by human activity more than any other process; understanding topographic evolution requires learning how geomorphic processes operate on human-sculpted landscapes. Comparison between Appalachian landscapes before and after MTR mining reveal critical differences in geomorphic processes and variables between unmined and mined landscapes. Incorporating these alterations into LEMs may allow assessment of reclamation strategies, mitigation of environmental harm, and the reduction of impacts from future mining as demand for critical minerals continues to grow.

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Data availability

Data will be made publicly and permanently available in a DOI-stamped FigShare reporitory upon submission of the revised manuscript.

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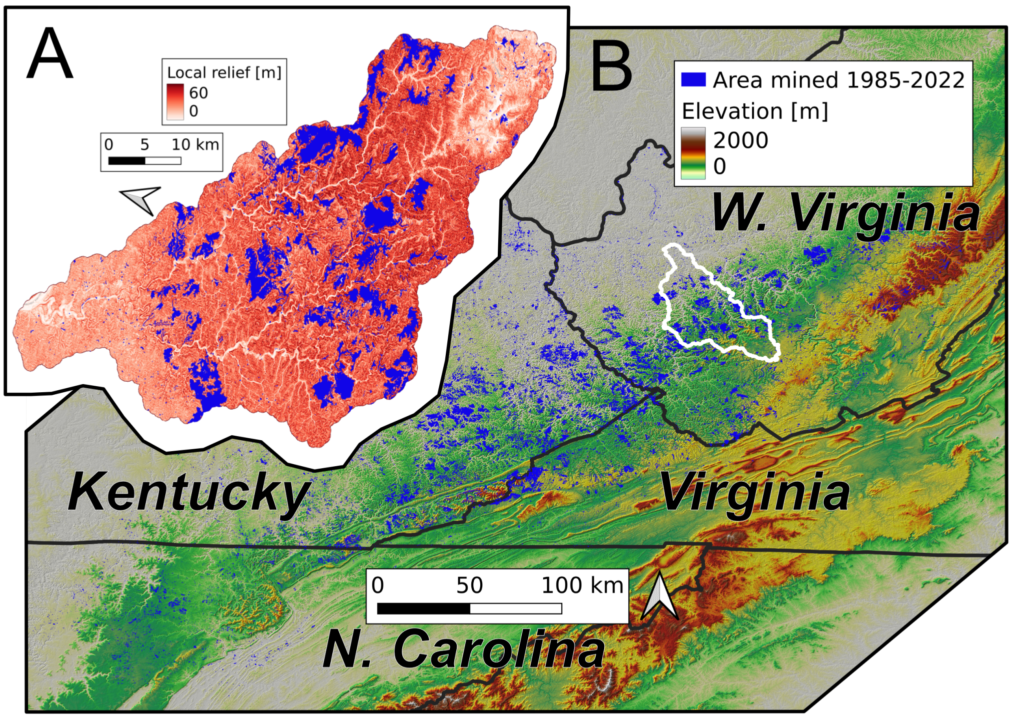

Figure 1: The AC region is characterized by steep-sided river valleys incised into the Appalachian Plateau. A) zoom-in of white polygon—the Coal River watershed—colored by local relief in a 150 m wide moving window and rotated for fit. Blue polygons show the extent of surface mining from 1985-2022 (2022 provisional update to dataset of (Pericak et al., 2018), downloaded from www.skytruth.org), the majority of which is concentrated in eastern Kentucky, southwestern Virginia, and southern West Virginia, USA. B) Shaded relief map of the AC region colored by elevation. Elevation data is from the U.S. Geological Survey National Elevation Dataset.

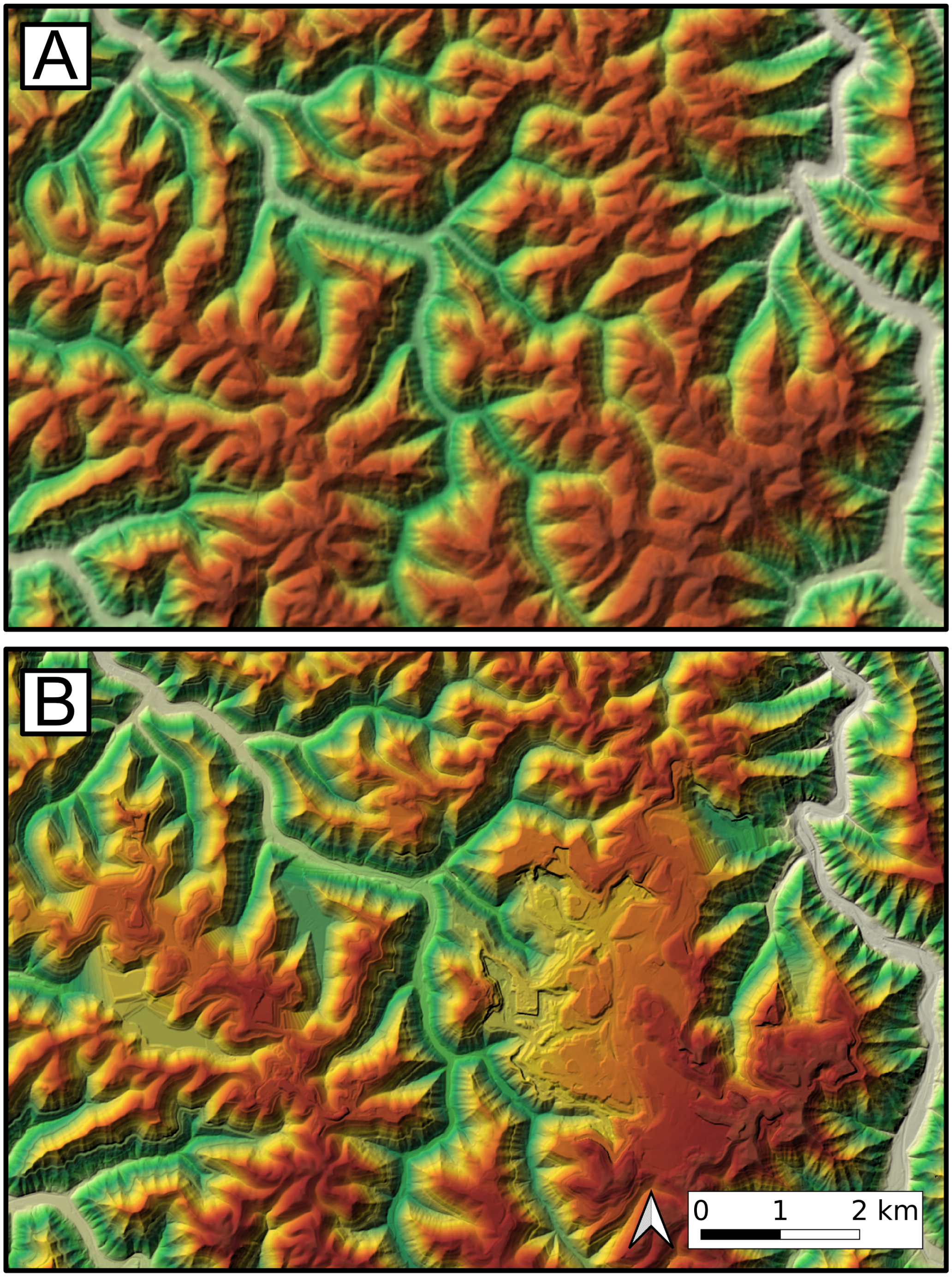

Figure 2: A typical view of the AC landscape before (A) and after (B) extensive MTR mining. The primary morphologic effects of MTR are the flattening and expansion of ridgetops and the filling of headwater streams. DEMs were produced by Ross et al. (2016); relief in this landscape is approximately 900 m.

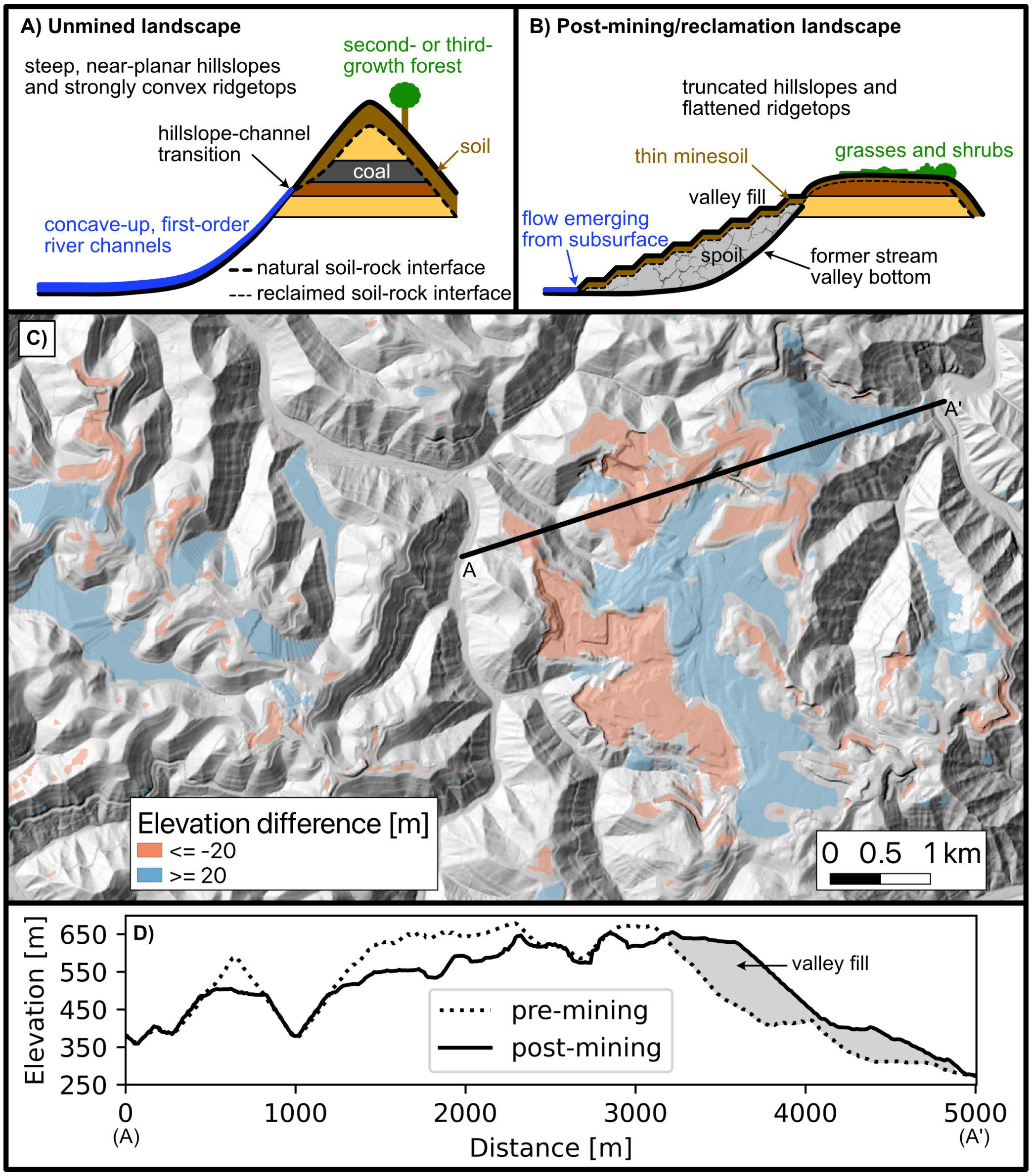

Figure 3: A) and B) Representative schematic cross-sections of unmined and mined/reclaimed landscapes, respectively. C) Lidar-derived DEM of an intensively mined area, with elevation differences between the post-mining and pre-mining topography shown in color overlays. Red areas indicate reduced elevation due to excavation of ridges, while blue areas indicate valley fill. D) Topographic cross-sections through the two DEMs showing differences between the pre-and post-mining landscapes. Fill is shown in gray shading.

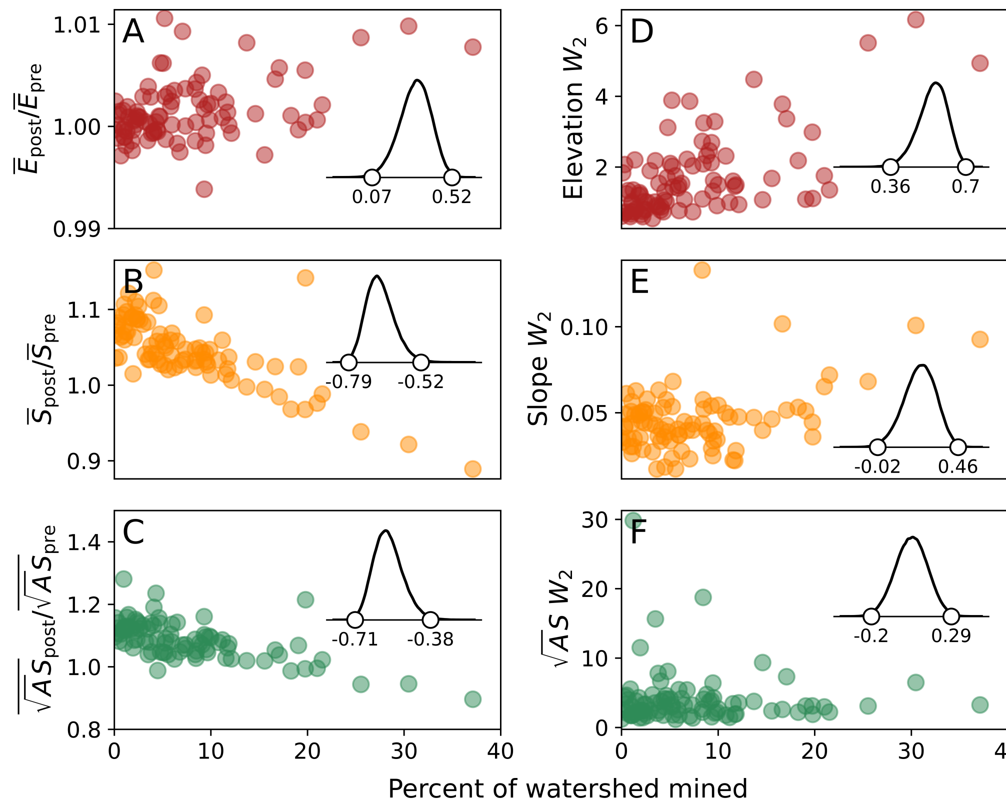

Figure 4: Comparisons between pre- and post-mining geomorphic characteristics of 88 HUC-12 watersheds with at least 90% coverage of pre- and post-mining elevation data. A–C show the influence of mining on the ratio of post- to pre-mining mean elevation, mean slope, and mean slope–area product, respectively. D–F show the Wasserstein distance (Lipp and Vermeesch, 2022) between the distributions of pre- and post-mining DEM pixels. Higher W_2 values indicate greater change. Inset plots show posterior distributions of the correlation coefficient found by Bayesian rank correlations (van Doorn et al., 2020). Labels report the 99% highest posterior density interval. An interval encompassing zero implies a low probability of correlation and vice versa.

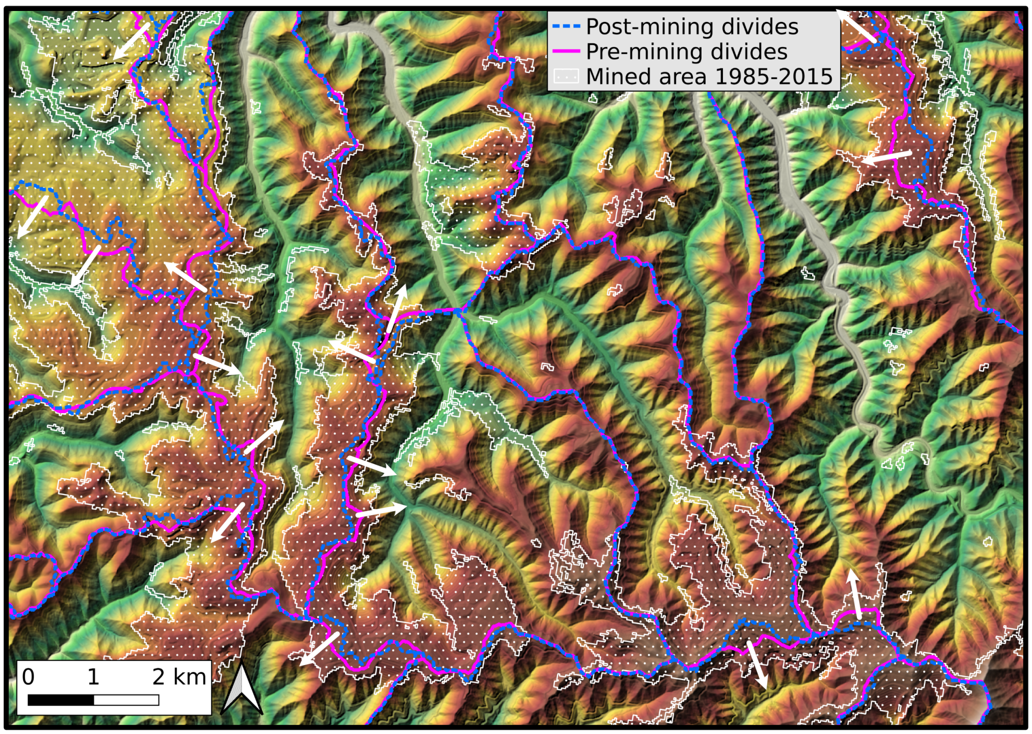

Figure 5: Mining-induced drainage divide migration. Drainage divides mapped from pre-mining and post-mining DEMs (pink solid line and blue dashed line, respectively) using TopoToolbox 2 (Schwanghart and Scherler, 2014). Divides have not moved in places that have not experienced mining. Mined areas (white dotted regions) coincide with up to hundreds of meters of divide motion (indicated schematically by white arrows). Mined area data is from Pericak et al. (2018).

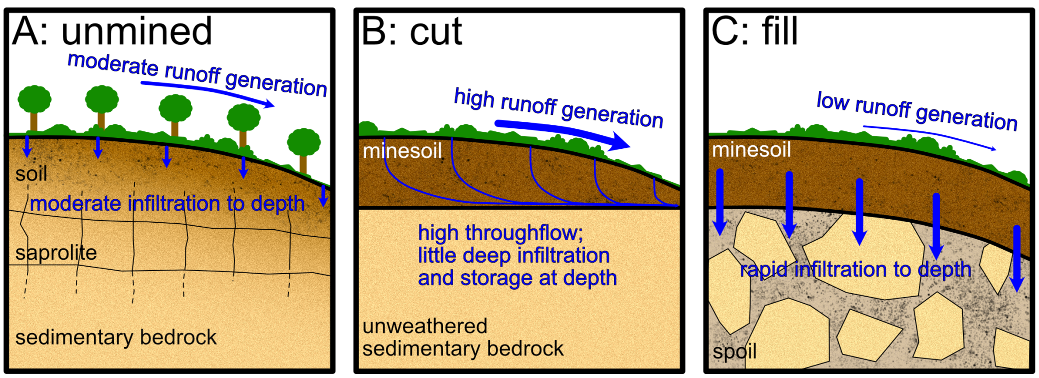

Figure 6: Schematic demonstrating differences in surface water balance among unmined (A), cut (B), and filled (C) portions of the lanscape. Differences in subsurface properties influence the relative efficiency of runoff generation. Cut portions of the landscape generate more runoff per unit rainfall than unmined land, whereas filled portions generate less runoff than unmined land.

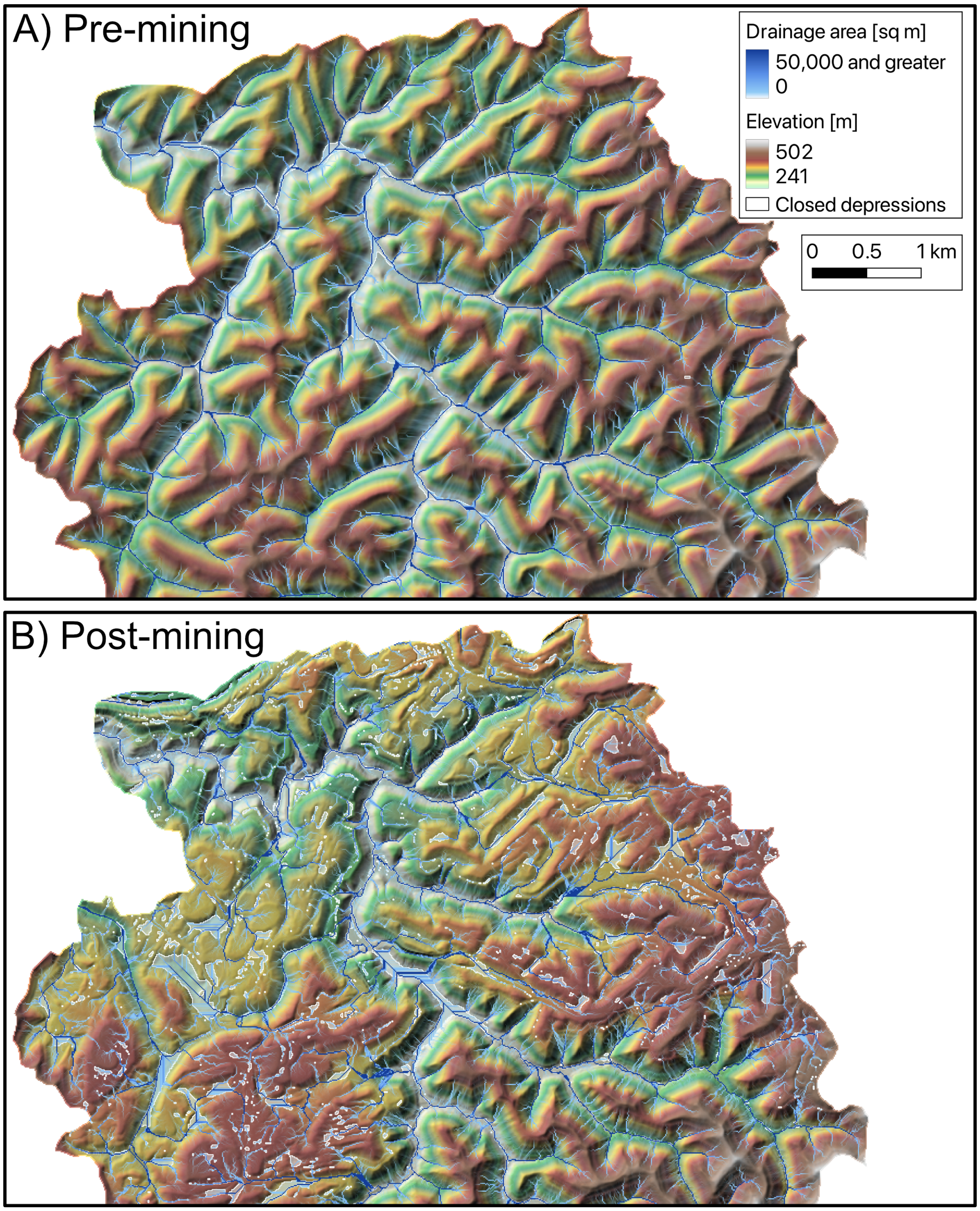

Figure 7: Differences in flow routing and accumulation across the pre-mining (A) and post-mining (B) landscapes of the Mud River, WV using D∞ routing (Tarboton, 1997; Barnes, 2017). Mining rearranges catchment areas at multiple scales and creates broad, flat regions that host many large closed depressions.

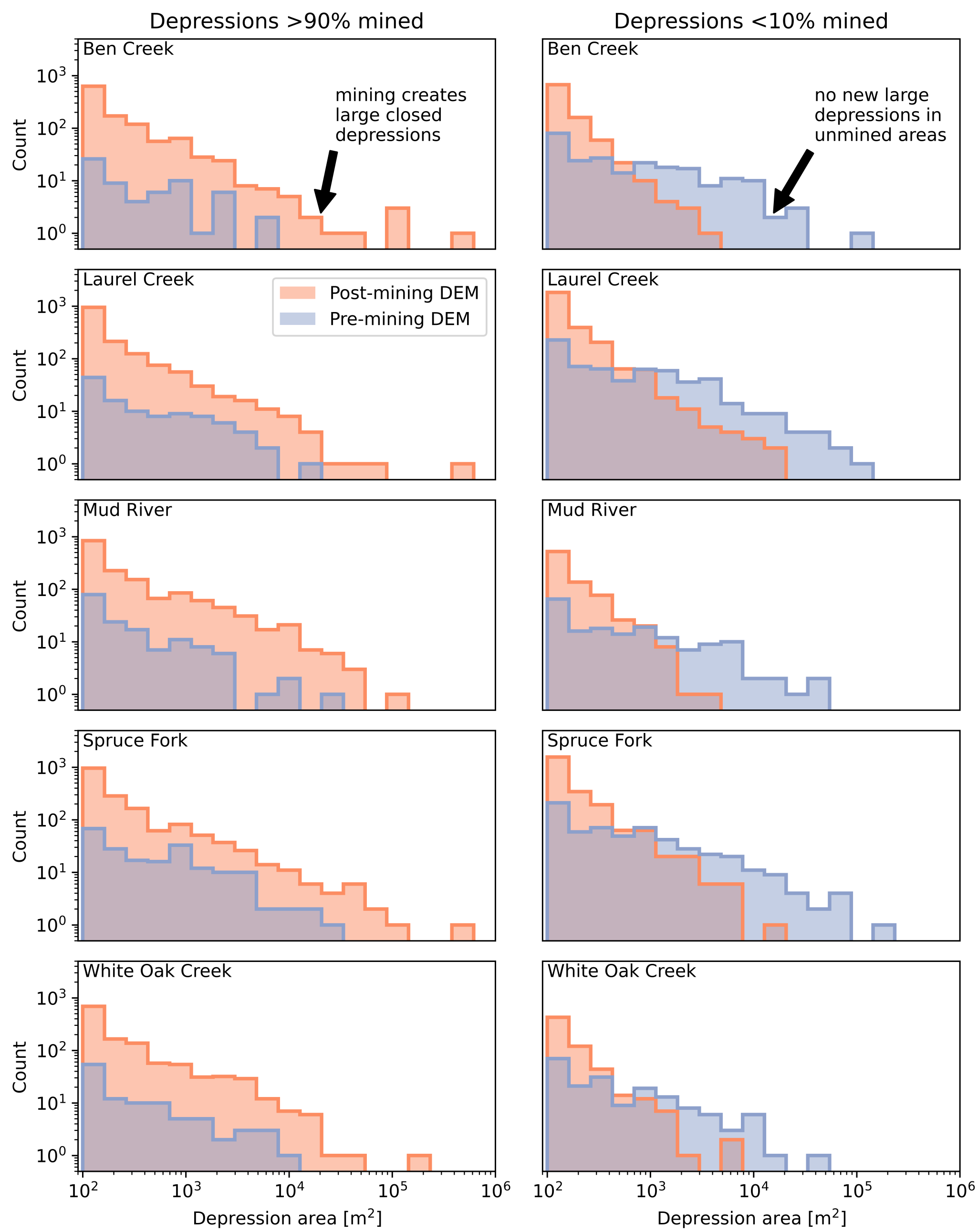

Figure 8: Histograms of closed depressions in pre- (blue) and post-mining (orange) DEMs for five HUC12 river basins. Separating depressions by the extent to which they overlap areas of the DEM identified as having undergone mining (Pericak et al., 2018) shows that mined areas are more likely to exhibit the formation of large ($> 10^4$) closed depressions, likely due to the flattening of much of the land surface. In unmined areas we do not observe the formation of large closed depressions, indicating that their formation in mined areas is not an artifact of differences between the two DEMs.

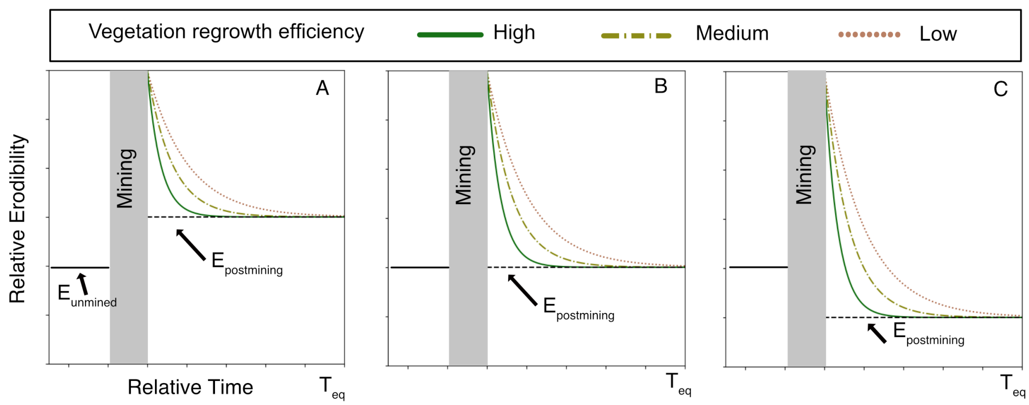

Figure 9: Proposed scenarios for the potential effects of material property changes on erodibility of mined landscapes under different vegetation regrowth efficiencies. Solid black lines show pre-mining erodibility E_{unmined}. Once mining occurs (grey boxes), landscapes experience increased erodibility that decreases over time to a new equilibrium erodibility $E_{\text{postmining}}$ that is either greater than (A), equal to (B), or less than (C) the pre-mining erodibility. The relationship between E_{unmined} and $E_{\text{postmining}}$ is set by mining-induced changes to soil mechanical properties like porosity, texture, bulk density, and cohesion in ways that are currently poorly understood. Line color and style indicates high, medium, or low vegetation regrowth efficiencies, which alter the time T_{eq} that it takes to reach the new equilibrium erodibility. We hypothesize that (A) is the most likely case, meaning that even with full vegetation recovery, material property changes prevent landscapes from recovering to their pre-mining erodibility over timescales less than that required to completely replace the soil column.