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

Charles M. Shobe[a,b], Samuel J. Bower[a], Aaron E. Maxwell[a], Rachel C. Glade[c], Nacere M. Samassi[c]

[a]*Department of Geology and Geography, West Virginia University, Morgantown, WV, USA*
[b]*Now at: United States Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA*
[c]*Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY, USA*

CMS: charles.shobe@usda.gov (corresponding author)

SJB: sjb00020@mix.wvu.edu

AEM: aaron.maxwell@mail.wvu.edu

RCG: rachel.glade@rochester.edu

NMS: nsamassi@ur.rochester.edu

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Graphical Abstract

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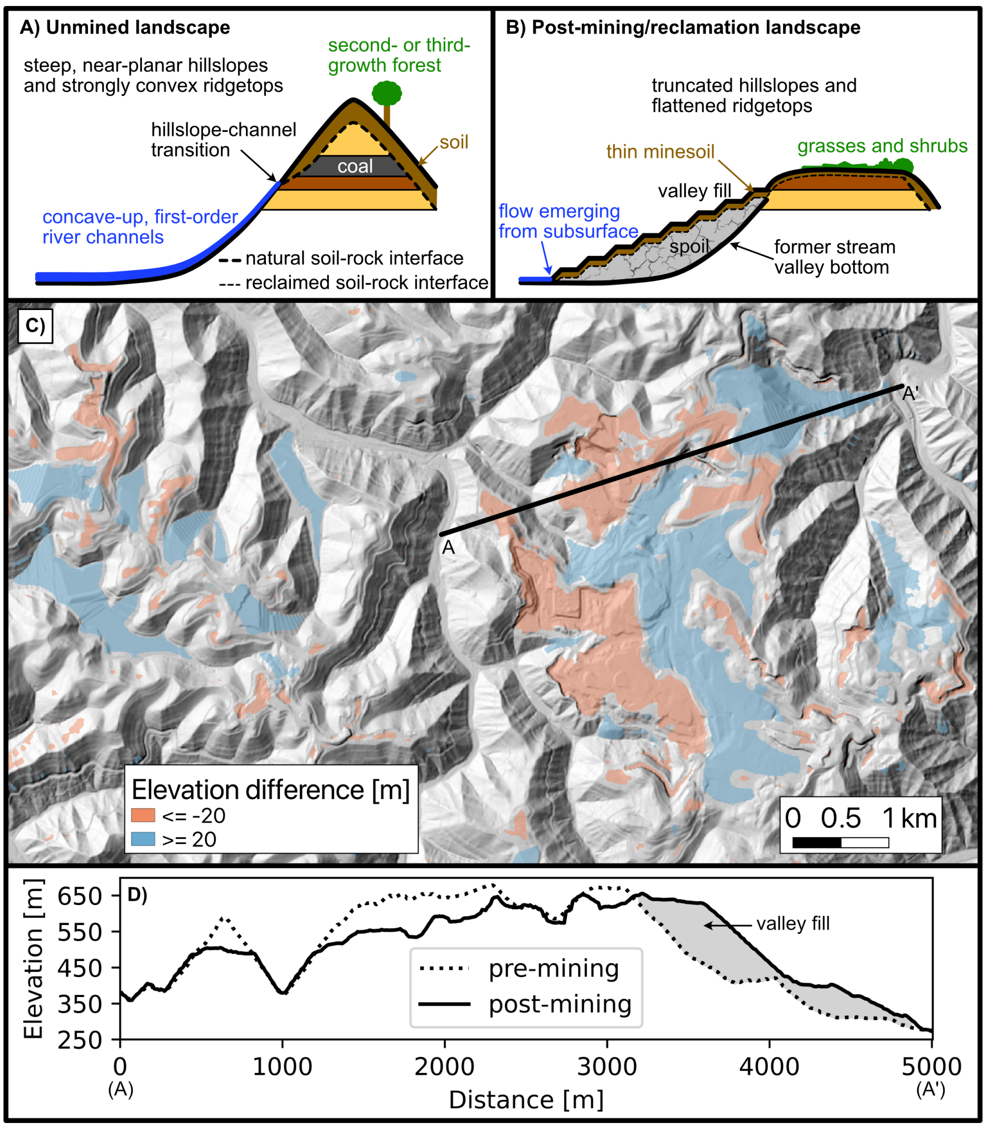

Highlights

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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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[a]*Department of Geology and Geography, West Virginia University, Morgantown, WV, USA*
[b]*Now at: United States Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA*
[c]*Department of Earth and Environmental Sciences, University of Rochester, Rochester, NY, USA*

Abstract

Surface mining may be humanity's most tangible impact on Earth's surface and will become more prevalent as the energy transition progresses. Prediction of post-mining landscape change can help mitigate environmental damage, 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/valley fill (MTR/VF) coal mining in the Appalachian Coalfields, USA. The future of MTR/VF landscapes is unclear because mining's effects on geomorphic processes are poorly understood. We use geospatial analysis—leveraging the existence of pre- and post-MTR/VF elevation models—and synthesis of literature to ask how MTR/VF alters topography, hydrology, and land-surface erodibility and how these changes could be incorporated into numerical models of post-MTR/VF landscape evolution.

*charles.shobe@usda.gov

MTR/VF reduces slope and area–slope product, and rearranges drainage divides. Creation of closed depressions alters flow routing and casts doubt on the utility of models that assume steady flow. MTR/VF 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 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 waste rock fills and mine soils also likely experience reduced erosion resistance. Our analysis suggests three necessary ingredients for numerical modeling of post-MTR/VF landscape change: 1) accurate routing and accumulation of unsteady overland flow and accompanying sediment across low-gradient, depression-rich, engineered landscapes, 2) separation of the landscape into cut, filled, and unmined regions, and 3) incorporation of vegetation recovery trajectories. 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 (Pelletier et al., 2015; Lazarus and Goldstein, 2019; Barnhart et al., 2020b).

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 (Vidal et al., 2013; Sonter et al., 2018; Sovacool et al., 2020; 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., 2019, 2020c,d,e) 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 learn 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/valley fill (MTR/VF) 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/VF landscape evolution—and the evolution of disturbed landscapes in general—by leveraging the unique unnatural experiment of MTR/VF-modified landscapes to derive insight into human alterations to geomorphic processes and variables. We use geospatial analysis of pre- and post-MTR/VF digital elevation models (DEMs), in conjunction with synthesis of existing literature, to assess the effects of MTR/VF 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/VF 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/VF 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/VF and the landscape of Appalachia are inextricably intertwined, with many MTR/VF mining procedures and mine reclamation regulations existing because of characteristics unique to the Appalachian landscape. Due to the uniqueness of the AC region's topography, climate, geology, and regulations governing mine reclamation, Appalachian MTR/VF 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/VF 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/VF mining occurred, and continues to occurr, in southern West Virginia, eastern 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. MTR/VF mining is not uniformly concentrated across the AC region, but typically targets Pennsylvanian coals in the Pocahontas Basin of southern West Virginia, eastern Kentucky, and southwestern Virginia (Fig. 1; Fedorko and Blake, 1998; Eriksson and Daniels, 2021).

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). It is best thought of as a relatively resistant, caprock-defined surface undergoing fluvial incision and hillslope response that has the potential to produce increasing relief over time (Morisawa, 1962; DiBiase et al., 2018; Gallen, 2018; Portenga et al., 2019). Cosmogenic nuclide measurements indicate that river-basin-averaged erosion rates may be up to 2–3 times faster than ridgetop outcrop lowering rates in parts of the region (Hancock and Kirwan, 2007; Portenga et al., 2019).

Such disequilibrium leads to a steep, highly erosive landscape where rivers are carving deep, narrow valleys into bedrock (Figs. 1 and 2). Widespread landsliding (e.g., Outerbridge, 1987) indicates that hillslopes are kept at or near their stability threshold by the pace of river incision and the relatively resistant plateau caprock units. Landsliding strips weathered bedrock and colluvium from hillslopes (Parker et al., 2016) and delivers pulses of sediment to bedrock-alluvial river channels.

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/VF mining has the most dramatic effects on the land surface. In MTR/VF mining, miners use explosives and heavy excavating equipment to remove overlying rock 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/VF yields enormous volumes of fractured waste rock, often known as spoil. 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/VF 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 landscapes 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/VF-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 (Figs. 1 and 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; 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 approximately 0.5 m/m slope and near-zero slope (Fig 2; Reed and Kite, 2020). 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/VF 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 environmental impacts of MTR/VF

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/VF 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/VF's negative environmental effects depend on geomorphic process dynamics. The efficiency of erosion on reclaimed mines controls sediment supply to nearby streams (Bonta, 2000), determining the response of streambeds (Jaeger, 2015) and aquatic ecosystems (Bernhardt and Palmer, 2011) to upstream mining and potentially influencing the likelihood of aggradation-driven flooding. 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/VF 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/VF mining. Each 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/VF 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/VF-induced changes to topography critical for forecasting the evolution of mined lands.

3.1. Alterations observed in prior work

MTR/VF 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 alters 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/VF-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/VF 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/VF 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 drainage area and slope (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 area–slope 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.

3.2. Alterations observed in this study

3.2.1. Elevation, slope, and drainage area

To further quantify the influence of mining's spatial extent on topography, we analyze ratios of the post- to pre-mining mean elevation, slope, and area–slope product ($\sqrt{A}S$) 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). In contrast with prior work (Jaeger and Ross, 2021), we take the square root of A because erosive power tends to scale sub-linearly with drainage area (e.g., Leopold and Maddock, 1953; Howard and Kerby, 1983; Whipple and Tucker, 1999). 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 as represented by elevation, slope, and $\sqrt{A}S$. We conducted Bayesian rank correlations (van Doorn et al., 2020), which allow exploration of nonparametric relationships between variables in a probabilistic framework. We consider a correlation robust if the 99% highest posterior density interval (HPDI; the narrowest interval containing 99% of the probability) for the posterior distribution of the correlation coefficient (insets in Fig. 4) does not include zero—in other words, if a non-zero correlation coefficient is likely. Drainage area was determined with D8 flow routing and the PriorityFlood algorithm in the Landlab modeling toolkit to route flow through closed depressions (Barnes, 2017; Barnhart et al., 2020a).

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 area–slope product $\sqrt{A}S$ follows a similar pattern; it 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 unity at about 10-20% mined catchment area. Overall our results indicate strong control of mining over mean catchment statistics, but the direction of the effect depends on how much of the watershed is mined.

We also analyzed the Wasserstein Distance (W_2; Lipp and Vermeesch, 2022) between the pre- and post-mining distribution of elevation, slope, and area–slope product in each HUC-12 catchment. This is effectively a cost function that measures the relative difficulty of turning the pre-mining distribution into the post-mining distribution. It is a useful addition to our study 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 magnitude and direction of that change depend heavily on the extent of mining in the watershed.

Based on analysis of slope and area–slope 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).

3.2.2. Drainage divide reorganization

MTR/VF-induced modifications to elevation cause another important but previously undocumented landscape change: the anthropogenic reorganization of drainage divides at rates that far outpace those due to natural processes. Planview drainage divide migration, driven by differences in cross-divide erosion rates (Whipple et al., 2017), is typically only observable over geologic time—except in rare instances of sudden drainage capture (e.g., Dahlquist et al., 2018). By flattening the ridgetops that previously defined drainage basin boundaries, MTR/VF can redistribute drainage area among basins over years to decades. The direction of divide migration depends only on the results of mining and reclamation processes instead of on the cross-divide erosion rate contrasts that dictate natural divide migration. We use TopoToolbox2 (Schwanghart and Scherler, 2014) to compare drainage basin configurations between pre- and post-MTR/VF DEMs in the context of remotely sensed mine location data (Pericak et al., 2018). These analyses use D8 flow routing with the DEMs "carved" to allow flow through closed depressions (Schwanghart et al., 2013). 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 faster than typical divide migration rates in unmodified postorogenic landscapes (Beeson et al., 2017). MTR/VF mining may represent the most extensive and dramatic case of anthropogenic headwater basin reorganization in the world.

The implications of this finding for post-mining landscapes are substantial. Major, instantaneous shifts in drainage divide location reallocate water, sediment, and mining-related pollutants among basins. MTR/VF-driven divide migration may therefore exert an important control on the geomorphic and environmental impacts of mining on headwater streams based on whether those streams experience increases or decreases in drainage area; this possibility has not to our knowledge been investigated. Over millennial and longer timescales, anthropogenic drainage reorganization has the potential to affect the spatial distribution of sediment export from mined regions and to place the landscape onto novel trajectories of geomorphic evolution. We might for example expect basins that lost drainage area due to MTR/VF-driven divide migration to develop higher near-divide relief and erosion rates than basins that gained drainage area, thereby driving a geomorphic response that would not have occurred without mining. The effects of mining-driven drainage reorganization over both human and geologic timescales warrant more systematic future investigation.

3.2.3. Closed depressions and landscape connectivity

Connectivity, or the efficiency with which water, sediment, and other constituents travel through the geomorphic system, is a key control on landscape evolution and ecosystem function (e.g., Wohl et al., 2019). To assess the influence of MTR/VF mining on geomorphic connectivity, we use a flow routing algorithm with D∞ routing (Tarboton, 1997; Barnes, 2017; Barnhart et al., 2020a) to identify closed depressions across mined and unmined DEMs for five study watersheds (Figs. 6–8). We document dramatic increases in the number, area, and volume of closed depressions due to MTR/VF mining; we interpret these depressions to be primarily stormwater and sediment retention structures (e.g., Reed and Kite, 2020). Post-MTR/VF DEMs exhibit much greater numbers of areally extensive ($> 10^4$ m^2) closed depressions than do pre-MTR/VF DEMs, an effect that exists only in the parts of the landscape that have experienced mining (Figs. 6 and 7) and that therefore is not due only to differences in how the two sets of DEMs were derived. The total volume of closed depressions, a rough proxy for the total surface water and sediment storage potential in the landscape, is orders of magnitude greater in post-mining watersheds than pre-mining ones (Fig. 8). Because natural closed depressions are uncommon in the AC region, post-MTR/VF landscapes have the potential for much greater water and sediment storage—and much lower geomorphic connectivity—than unmined landscapes. However, because mining activity is concentrated at high elevations, a large proportion of these anthropogenic closed depressions are located on summit flats upslope of likely erosion hotspots (Fig. 6), which tend to be concentrated at the steep margins of mined landscapes. Differences in connectivity between unmined and mined areas may therefore vary as a function of topographic position. Closed depressions, and the extent to which they reconnect to the surrounding landscape over time, is likely to exert a significant control on post-MTR landscape evolution (e.g., Lai and Anders, 2018).

3.3. 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 cluster tightly in area–slope space in an unmined Appalachian watershed, constructed channel heads in a nearby mined watershed span four orders of magnitude in drainage area, nearly two orders of magnitude in slope, and cannot be defined by any one area–slope 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 post-MTR/VF 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/VF-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 generation of many large closed depressions poses significant challenges for modeling. If depressions are effective at reducing connectivity and storing sediment, the detachment-limited modeling framework will be inapplicable and models that explicitly conserve sediment mass (e.g., Shobe et al. (2017) as used in our companion paper) will be required. The rearrangement of topography due to MTR/VF mining adds further complexity due to the influence of topography on flow routing and basin hydrology.

4. Alterations to surface hydrology

Land-surface hydrology governs the rates and spatiotemporal patterns of erosion by flowing water, thought to be the primary means of mass export from MTR/VF-modified landscapes (e.g., Reed and Kite, 2020). We focus on surface water over groundwater dynamics because of its more direct connections to common LEMs, but acknowledge the importance and complexity of subsurface flow paths on MTR/VF 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) and threaten to reduce the applicability of common LEM approaches.

4.1. Observed alterations

MTR/VF 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 water management 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/VF 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 filled areas within mined landscapes due to differences in subsurface structure (Figs. 3 and 9).

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 filled 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 (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.

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-mining 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. 6) demonstrates the extent to which MTR/VF 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/VF 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 attempt to shape post-mining topography in ways that reduce the volume and velocity of overland flow (e.g., Toy and Black, 2000; DePriest et al., 2015). 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 MTR/VF mines.

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

MTR/VF-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 (e.g., Ferrari et al., 2009; McCormick et al., 2009)? 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 (Nippgen et al., 2017)? 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 some changes to overland flow accumulation that arise from restructuring of topography (e.g., changes in the location of drainage divides) 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 of differing surface and subsurface properties (i.e., cut versus fill areas) on the water balance. Because such simple LEMs contain the implicit assumption of steady 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.

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 MTR/VF mine complexes. We suggest that there is sufficient uncertainty around other aspects of reclaimed mines, ranging from the presence of older, underground mines (McCormick et al., 2009; 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 9). 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. 9). 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 effects of altered topography on flow routing, peak flood volumes, and erosive stresses. Flattening of previously steep hillslopes (Figs. 2 and 4), together with the creation of closed depressions (Figs. 6 – 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). Whether overland flow is treated explicitly or as a function of drainage area, the ubiquity of closed depressions and flat regions in post-MTR/VF landscapes elevates the importance of selecting appropriate schemes for flow routing and depression handling (e.g., Tarboton, 1997; Schwanghart et al., 2013; Cordonnier et al., 2019).

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. If the assumption that vegetation exerts a meaningful control on overland flow dynamics and erosion is correct, the vegetation recovery trajectory on reclaimed mines and its hydrologic effects may play an outsized role in determining the geomorphic future of mined lands.

The extent to which models of post-MTR/VF landscape change 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 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/VF 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/VF mining is by its very nature a process of altering surface and subsurface material properties: vegetation is removed (Fig. 10), overburden is blasted and crushed into waste rock, soil is moved and subsequently compacted, and 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 and erodibility.

5.1. Observed alterations

Mining and reclamation change bulk surface and near-surface material properties. 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 a greater 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-MTR/VF 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). Because VFs have a layer of cobbles and boulders at their base, their grain size distributions may coarsen significantly with depth (Michael et al., 2010). Finer grains, in conjunction with a decrease in cohesion, could lead to enhanced erosion and gullying during runoff events due to reduced thresholds for sediment motion (Reed and Kite, 2020). VFs composed in large part of coal refuse instead of waste rock are especially fine-grained and susceptible to erosion (Daniels and Stewart, 2000; Salam et al., 2020). 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 several years post-reclamation (Mukhopadhyay et al., 2016). After many decades or longer, 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 post-mining erosion 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 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 diversity rarely return to pre-mining conditions even over multidecadal timescales (Latifovic et al., 2005; Franklin et al., 2012; Oliphant et al., 2017; Ross et al., 2021; Sena et al., 2021). A recent remote sensing study of long-term post-MTR/VF vegetation recovery over 30 years in Central Appalachia found that only about 8% of post-mined sites recover to 95% of their original condition as measured by a variety of spectral vegetation indices (Thomas et al., 2022). Tree canopy height in mined areas recovers more slowly than deforested but unmined areas of similar landscapes, and is not expected to approach unmined canopy height conditions for at least 50 years after mining (Ross et al., 2021). 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 (Franklin et al., 2012; Adams et al., 2017b; Sena et al., 2021; Thomas et al., 2022). MTR/VF mines regenerate much of their greenness by approximately 20 years after the cessation of mining (Fig. 10; Ross et al., 2021; Thomas et al., 2022), but they do so without fully rebuilding the forest ecosystems that would restore hydrologic function and erosion resistance to the post-mining landscape.

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). Ground cover plants can compete with tree seedlings for moisture and sunlight, inhibiting tree growth and the development of mature forest (Sena et al., 2021). Recent efforts to prioritize forest development, known as the "Forest Reclamation Approach" (FRA), have shown some promise in improving post-mining reforestation (Burger et al., 2018; Zipper et al., 2011). However, the general 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/VF 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 into LEMs 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 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 $\geq 10^3$ year timescales 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/VF 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). 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/VF landscapes. On average, over the sub-millennial timescales for which 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. 11). 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 even higher during active mining (Michael et al., 2010), 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/VF 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/VF 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. 11A), equal to (Fig. 11B), or less than (Fig. 11C) 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.

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/VF 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/VF mining process. In addition to improving our understanding of the role of specific material properties, substantial increases in heterogeneity of properties such as grain size, shape, cohesion, and bulk density at MTR/VF sites (Topp et al., 2010; Feng et al., 2019) emphasize 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 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 comparing mined versus unmined sites and chronosequences of reclaimed mines could better constrain 1) how MTR/VF affects these properties and 2) how they influence 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/VF vegetation and material property disturbances into models of subsequent landscape change. While we have introduced a heuristic framework (Fig. 11) that we explore in our companion paper (Bower et al., in review), the success of post-MTR/VF 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 MTR/VF mining, combined with synthesis of the literature, reveals key ways in which MTR/VF changes geomorphic processes and illuminates three probably necessary ingredients for models of post-mining 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 potentially unsteady flow—as well as the sediment it carries—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), or at least to parameterize the aggregate effects of unsteady flow. 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/VF 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 status 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/VF 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 consistent with 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.

Though MTR/VF coal mining represents only one type of surface mining, our findings might help identify geomorphic and environmental impacts of other types of surface mining both past and future. Global maps of past and current mining activity (Tang and Werner, 2023) emphasize the great extent and wide variety of mined landscapes, while the global distribution of critical minerals (Labay et al., 2017; Schulz et al., 2017) provides insight into where the future expansion of surface mining might be most dramatic. Developing LEMs that adequately incorporate mining-induced changes to landscape process and form across these diverse tectonic, climatic, lithologic, and ecologic settings is essential to predicting—and reducing—the geomorphic impact of mining to support the ongoing energy transition. Modeling post-mining geomorphic change before mining occurs, for example as part of environmental impact studies, may help avoid long-term and cumulative impacts that are often overlooked in shorter-term analyses (Sonter et al., 2023).

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. Comparing Appalachian landscapes before and after MTR/VF mining reveals critical differences in geomorphic processes and variables between unmined and mined landscapes. Incorporating these alterations into LEMs may allow assessment of reclamation strategies and mitigation of environmental harm from future mining as demand for critical minerals continues to grow.

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Data availability

All data not already publicly archived by agencies/researchers cited throughout the paper, as well as code for analyses, are archived in Zenodo at https://dx.doi.org/10.5281/zenodo.10059513 (Shobe, 2023).

References

Abrahams, A.D., Parsons, A.J., Wainwright, J., 1994. Resistance to overland flow on semiarid grassland and shrubland hillslopes, walnut gulch, southern arizona. Journal of Hydrology 156, 431–446.

Adams, J.M., Gasparini, N.M., Hobley, D.E., Tucker, G.E., Hutton, E.W., Nudurupati, S.S., Istanbulluoglu, E., 2017a. The landlab v1. 0 overlandflow component: a python tool for computing shallow-water flow across watersheds. Geoscientific Model Development 10, 1645–1663.

Adams, M.B., Angel, P., Barton, C., Burger, J., Davis, J., French, M., et al., 2017b. The forestry reclamation approach: guide to successful reforestation of mined lands. Gen Tech Rep NRS-169 119.

Anders, A.M., Lai, J., Marshak, S., 2022. Development of foreland intracratonic plateaus (ozark plateau and appalachian plateaus): A consequence of topographic inversion due to erosion of adjacent fold-thrust belts. Tectonics 41.

Asghari, S., Abbasi, F., Neyshabouri, M.R., 2011. Effects of soil conditioners on physical quality and bromide transport properties in a sandy loam soil. Biosystems engineering 109, 90–97.

Barnes, R., 2017. Parallel non-divergent flow accumulation for trillion cell digital elevation models on desktops or clusters. Environmental Modelling & Software 92, 202–212.

Barnhart, K.R., Glade, R.C., Shobe, C.M., Tucker, G.E., 2019. Terrainbento 1.0: a python package for multi-model analysis in long-term drainage basin evolution. Geoscientific Model Development 12, 1267–1297.

Barnhart, K.R., Hutton, E.W., Tucker, G.E., Gasparini, N.M., Istanbulluoglu, E., Hobley, D.E., Lyons, N.J., Mouchene, M., Nudurupati, S.S., Adams, J.M., et al., 2020a. Landlab v2. 0: A software package for earth surface dynamics. Earth Surface Dynamics 8, 379–397.

Barnhart, K.R., Tucker, G.E., Doty, S.G., Glade, R.C., Shobe, C.M., Rossi, M.W., Hill, M.C., 2020b. Projections of landscape evolution on a 10,000 year timescale with assessment and partitioning of uncertainty sources. Journal of Geophysical Research: Earth Surface 125, e2020JF005795.

Barnhart, K.R., Tucker, G.E., Doty, S.G., Shobe, C.M., Glade, R.C., Rossi, M.W., Hill, M.C., 2020c. Inverting topography for landscape evolution model process representation: 1. conceptualization and sensitivity analysis. Journal of Geophysical Research: Earth Surface 125, e2018JF004961.

Barnhart, K.R., Tucker, G.E., Doty, S.G., Shobe, C.M., Glade, R.C., Rossi, M.W., Hill, M.C., 2020d. Inverting topography for landscape evolution model process representation: 2. calibration and validation. Journal of Geophysical Research: Earth Surface 125, e2018JF004963. doi:https://doi.org/10.1029/2018JF004963.

Barnhart, K.R., Tucker, G.E., Doty, S.G., Shobe, C.M., Glade, R.C., Rossi, M.W., Hill, M.C., 2020e. Inverting topography for landscape evolution model process representation: 3. determining parameter ranges for select mature geomorphic transport laws and connecting changes in fluvial erodibility to changes in climate. Journal of Geophysical Research: Earth Surface 125, e2019JF005287.

Beeson, H.W., McCoy, S.W., Keen-Zebert, A., 2017. Geometric disequilibrium of river basins produces long-lived transient landscapes. Earth and Planetary Science Letters 475, 34–43.

Bell, J.C., Daniels, W.L., Zipper, C.E., 1989. The practice of "approximate original contour" in the central appalachians. i. slope stability and erosion potential. Landscape and Urban Planning 18, 127–138.

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, 8115–8122.

Bernhardt, E.S., Palmer, M.A., 2011. The environmental costs of mountaintop mining valley fill operations for aquatic ecosystems of the central appalachians. Annals of the New york Academy of Sciences 1223, 39–57.

Bond, S., Kirkby, M.J., Johnston, J., Crowle, A., Holden, J., 2020. Seasonal vegetation and management influence overland flow velocity and roughness in upland grasslands. Hydrological Processes 34, 3777–3791.

Bonta, J.V., 2000. Impact of coal surface mining and reclamation on suspended sediment in three ohio watersheds. JAWRA Journal of the American Water Resources Association 36, 869–887.

Bower, S.J., Shobe, C.M., Maxwell, A.E., Campforts, B., in review. The uncertain future of mountaintop-removal-mined landscapes 2: Modeling the influence of topography and vegetation. Geomorphology xx, xxxx–xxxx.

Brooks, A.C., Ross, M.R., Nippgen, F., McGlynn, B.L., Bernhardt, E.S., 2019. Excess nitrate export in mountaintop removal coal mining watersheds. Journal of Geophysical Research: Biogeosciences 124, 3867–3880.

Bunte, K., Poesen, J., 1993. Effects of rock fragment covers on erosion and transport of noncohesive sediment by shallow overland flow. Water resources research 29, 1415–1424.

Burger, J.A., Zipper, C.E., et al., 2018. How to restore forests on surface-mined land .

Bussler, B., Byrnes, W., Pope, P., Chaney, W., 1984. Properties of minesoil reclaimed for forest land use. Soil Science Society of America Journal 48, 178–184.

Cassel, M., Lavé, J., Recking, A., Malavoi, J.R., Piégay, H., 2021. Bedload transport in rivers, size matters but so does shape. Scientific Reports 11, 1–11.

Chen, J., Li, K., Chang, K.J., Sofia, G., Tarolli, P., 2015. Open-pit mining geomorphic feature characterisation. International Journal of Applied Earth Observation and Geoinformation 42, 76–86.

Collins, D.B.G., Bras, R., Tucker, G.E., 2004. Modeling the effects of vegetation-erosion coupling on landscape evolution. Journal of Geophysical Research: Earth Surface 109.

Cordonnier, G., Bovy, B., Braun, J., 2019. A versatile, linear complexity algorithm for flow routing in topographies with depressions. Earth Surface Dynamics 7, 549–562. URL: https://esurf.copernicus.org/articles/7/549/2019/, doi:10.5194/esurf-7-549-2019.

Coulthard, T.J., Neal, J.C., Bates, P.D., Ramirez, J., de Almeida, G.A., Hancock, G.R., 2013. Integrating the lisflood-fp 2d hydrodynamic model with the caesar model: implications for modelling landscape evolution. Earth Surface Processes and Landforms 38, 1897–1906.

Cunez, F.D., Patel, D., Glade, R., 2023. How particle shape affects granular segregation in industrial and geophysical flows .

Dahlquist, M.P., West, A.J., Li, G., 2018. Landslide-driven drainage divide migration. Geology 46, 403–406.

Daniels, W.L., Stewart, B.R., 2000. Reclamation of appalachian coal refuse disposal areas. Reclamation of drastically disturbed lands 41, 433–459.

Daniels, W.L., Zipper, C.E., et al., 2010. Creation and management of productive minesoils .

Davy, P., Croissant, T., Lague, D., 2017. A precipiton method to calculate river hydrodynamics, with applications to flood prediction, landscape evolution models, and braiding instabilities. Journal of geophysical research: earth surface 122, 1491–1512.

DePriest, N.C., Hopkinson, L.C., Quaranta, J.D., Michael, P.R., Ziemkiewicz, P.F., 2015. Geomorphic landform design alternatives for an existing valley fill in central appalachia, usa: Quantifying the key issues. Ecological Engineering 81, 19–29.

DiBiase, R.A., Denn, A.R., Bierman, P.R., Kirby, E., West, N., Hidy, A.J., 2018. Stratigraphic control of landscape response to base-level fall, young womans creek, pennsylvania, usa. Earth and Planetary Science Letters 504, 163–173.

Dickens, P.S., Minear, R.A., Tschantz, B.A., 1989. Hydrologic alteration of mountain watersheds from surface mining. Journal (Water Pollution Control Federation) , 1249–1260.

Dietrich, W.E., Bellugi, D., Real de Asua, R., 2001. Validation of the shallow landslide model, shalstab, for forest management. Land use and watersheds: human influence on hydrology and geomorphology in urban and forest areas 2, 195–227.

Doane, T.H., Edmonds, D., Yanites, B.J., Lewis, Q., 2021. Topographic roughness on forested hillslopes: a theoretical approach for quantifying hillslope sediment flux from tree throw. Geophysical Research Letters 48, e2021GL094987.

van Doorn, J., Ly, A., Marsman, M., Wagenmakers, E.J., 2020. Bayesian rank-based hypothesis testing for the rank sum test, the signed rank test, and spearman's ρ. Journal of Applied Statistics 47, 2984–3006.

Duque, J.M., Zapico, I., Oyarzun, R., García, J.L., Cubas, P., 2015. A descriptive and quantitative approach regarding erosion and development of landforms on abandoned mine tailings: New insights and environmental implications from se spain. Geomorphology 239, 1–16.

Emmett, W.W., 1970. The hydraulics of overland flow on hillslopes. volume 662. US Government Printing Office.

EPA, U., 2011. The effects of mountaintop mines and valley fills on aquatic ecosystems of the central appalachian coalfields. Washington, DC .

Eriksson, K.A., Daniels, W.L., 2021. Environmental implications of regional geology and coal mining in the appalachians, in: Appalachia's Coal-Mined Landscapes. Springer, pp. 27–53.

Evans, D.M., Zipper, C.E., Hester, E.T., Schoenholtz, S.H., 2015. Hydrologic effects of surface coal mining in appalachia (us). JAWRA Journal of the American Water Resources Association 51, 1436–1452.

Evans, K., Willgoose, G., 2000. Post-mining landform evolution modelling: 2. effects of vegetation and surface ripping. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 25, 803–823.

Fedorko, N., Blake, M., 1998. A geologic overview of mountaintop removal mining in west virginia. West Virginia Geological and Economic Survey .

Feng, Y., Wang, J., Bai, Z., Reading, L., 2019. Effects of surface coal mining and land reclamation on soil properties: A review. Earth-Science Reviews 191, 12–25.

Ferrari, J.R., Lookingbill, T., McCormick, B., Townsend, P., Eshleman, K., 2009. Surface mining and reclamation effects on flood response of watersheds in the central appalachian plateau region. Water Resources Research 45.

Fitzpatrick, L.G., 2018. Surface coal mining and human health: evidence from west virginia. Southern Economic Journal 84, 1109–1128.

Flowers, R.M., Ault, A.K., Kelley, S.A., Zhang, N., Zhong, S., 2012. Epeirogeny or eustasy? paleozoic–mesozoic vertical motion of the north american continental interior from thermochronometry and implications for mantle dynamics. Earth and Planetary Science Letters 317, 436–445.

Franklin, J.A., Zipper, C.E., Burger, J.A., Skousen, J.G., Jacobs, D.F., 2012. Influence of herbaceous ground cover on forest restoration of eastern us coal surface mines. New forests 43, 905–924.

Gabet, E.J., Mudd, S.M., 2010. Bedrock erosion by root fracture and tree throw: A coupled biogeomorphic model to explore the humped soil production function and the persistence of hillslope soils. Journal of Geophysical Research: Earth Surface 115.

Gallen, S.F., 2018. Lithologic controls on landscape dynamics and aquatic species evolution in post-orogenic mountains. Earth and Planetary Science Letters 493, 150–160.

Giam, X., Olden, J.D., Simberloff, D., 2018. Impact of coal mining on stream biodiversity in the us and its regulatory implications. Nature Sustainability 1, 176–183.

Glade, R.C., Fratkin, M.M., Pouragha, M., Seiphoori, A., Rowland, J.C., 2021. Arctic soil patterns analogous to fluid instabilities. Proceedings of the National Academy of Sciences 118, e2101255118.

Greer, B.M., Burbey, T.J., Zipper, C.E., Hester, E.T., 2017. Electrical resistivity imaging of hydrologic flow through surface coal mine valley fills with comparison to other landforms. Hydrological Processes 31, 2244–2260.

Guebert, M., Gardner, T., 1989. Unsupervised spot classification and infiltration rates on surface mined watersheds, central pennsylvania. Photogrammetric Engineering and Remote Sensing;(United States) 55.

Guebert, M.D., Gardner, T.W., 2001. Macropore flow on a reclaimed surface mine: infiltration and hillslope hydrology. Geomorphology 39, 151–169.

Haering, K.C., Daniels, W.L., Galbraith, J.M., 2004. Appalachian mine soil morphology and properties: Effects of weathering and mining method. Soil Science Society of America Journal 68, 1315–1325.

Hancock, G., 2004. The use of landscape evolution models in mining rehabilitation design. Environmental Geology 46, 561–573.

Hancock, G., 2021. A method for assessing the long-term integrity of tailings dams. Science of The Total Environment 779, 146083.

Hancock, G., Coulthard, T., 2022. Tailings dams: Assessing the long-term erosional stability of valley fill designs. Science of The Total Environment 849, 157692.

Hancock, G., Evans, K., Willgoose, G., Moliere, D., Saynor, M., Loch, R., 2000. Medium-term erosion simulation of an abandoned mine site using the siberia landscape evolution model. Soil Research 38, 249–264.

Hancock, G., Kirwan, M., 2007. Summit erosion rates deduced from 10be: Implications for relief production in the central appalachians. Geology 35, 89–92.

Hancock, G., Lowry, J., Coulthard, T., 2016. Long-term landscape trajectory—can we make predictions about landscape form and function for post-mining landforms? Geomorphology 266, 121–132.

Hancock, G., Lowry, J., Moliere, D., Evans, K., 2008. An evaluation of an enhanced soil erosion and landscape evolution model: a case study assessment of the former nabarlek uranium mine, northern territory, australia. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 33, 2045–2063.

Hancock, G., Saynor, M., Lowry, J., Erskine, W., 2020. How to account for particle size effects in a landscape evolution model when there is a wide range of particle sizes. Environmental Modelling & Software 124, 104582.

Hancock, G.R., Willgoose, G.R., 2021. Predicting gully erosion using landform evolution models: Insights from mining landforms. Earth Surface Processes and Landforms 46, 3271–3290.

Hawkins, J.W., 2004. Predictability of surface mine spoil hydrologic properties in the appalachian plateau. Groundwater 42, 119–125.

Hendryx, M., 2015. The public health impacts of surface coal mining. The Extractive Industries and Society 2, 820–826.

Hooke, R.L., 1994. On the efficacy of humans as geomorphic agents. GSA Today 4, 224–225.

Hooke, R.L., 1999. Spatial distribution of human geomorphic activity in the united states: comparison with rivers. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 24, 687–692.

Hooke, R.L., 2000. On the history of humans as geomorphic agents. Geology 28, 843–846.

Hopkinson, L.C., Lorimer, J.T., Stevens, J.R., Russell, H., Hause, J., Quaranta, J.D., Ziemkiewicz, P.F., 2017. Geomorphic landform design principles applied to an abandoned coal refuse pile in central appalachia. Journal of the American Society of Mining and Reclamation 6, 19–36.

Howard, A.D., Kerby, G., 1983. Channel changes in badlands. Geological Society of America Bulletin 94, 739–752.

International Energy Agency, 2022. The role of critical minerals in clean energy transitions .

Istanbulluoglu, E., Bras, R.L., 2005. Vegetation-modulated landscape evolution: Effects of vegetation on landscape processes, drainage density, and topography. Journal of Geophysical Research: Earth Surface 110.

Jaeger, K., Ross, M., 2021. Identifying geomorphic process domains in the synthetic landscapes of west virginia, usa. Journal of Geophysical Research: Earth Surface 126, e2020JF005851.

Jaeger, K.L., 2015. Reach-scale geomorphic differences between headwater streams draining mountaintop mined and unmined catchments. Geomorphology 236, 25–33.

Joann, M., Allan, J., 2021. Geomorphic perspectives on mining landscapes, hazards, and sustainability. Treatise on Geomorphology, 9, 106–143.

Johnson, C., Skousen, J., 1995. Minesoil properties of 15 abandoned mine land sites in West Virginia. Technical Report. Wiley Online Library.

Jorgensen, D.W., Gardner, T.W., 1987. Infiltration capacity of disturbed soils: Temporal change and lithologic control 1. JAWRA Journal of the American Water Resources Association 23, 1161–1172.

Labay, K.B., Bellora, M., Schulz, J., DeYoung, K., JH Jr, S., RR, I., Mauk, D., JL San Juan, C., 2017. Global distribution of selected mines, deposits, and districts of critical minerals .

Lai, J., Anders, A.M., 2018. Modeled postglacial landscape evolution at the southern margin of the laurentide ice sheet: Hydrological connection of uplands controls the pace and style of fluvial network expansion. Journal of Geophysical Research: Earth Surface 123, 967–984.

Latifovic, R., Fytas, K., Chen, J., Paraszczak, J., 2005. Assessing land cover change resulting from large surface mining development. International journal of applied earth observation and geoinformation 7, 29–48.

Lazarus, E.D., Goldstein, E.B., 2019. Is there a bulldozer in your model? Journal of Geophysical Research: Earth Surface 124, 696–699.

Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. US Geological Survey Professional Paper 252.

Lipp, A.G., Vermeesch, P., 2022. Comparing detrital age spectra, and other geological distributions, using the wasserstein distance .

Lowry, J., Narayan, M., Hancock, G., Evans, K., 2019. Understanding post-mining landforms: Utilising pre-mine geomorphology to improve rehabilitation outcomes. Geomorphology 328, 93–107.

Marston, R.A., 2010. Geomorphology and vegetation on hillslopes: Interactions, dependencies, and feedback loops. Geomorphology 116, 206–217.

Maxwell, A.E., Pourmohammadi, P., Poyner, J.D., 2020. Mapping the topographic features of mining-related valley fills using mask r-cnn deep learning and digital elevation data. Remote Sensing 12, 547.

Maxwell, A.E., Shobe, C.M., 2022. Land-surface parameters for spatial predictive mapping and modeling. Earth-Science Reviews 226, 103944.

Maxwell, A.E., Strager, M.P., 2013. Assessing landform alterations induced by mountaintop mining. Natural Science 5, 229–237.

McCormick, B.C., Eshleman, K.N., Griffith, J.L., Townsend, P.A., 2009. Detection of flooding responses at the river basin scale enhanced by land use change. Water Resources Research 45.

Merricks, T.C., Cherry, D.S., Zipper, C.E., Currie, R.J., Valenti, T.W., 2007. Coal-mine hollow fill and settling pond influences on headwater streams in southern west virginia, usa. Environmental Monitoring and Assessment 129, 359–378.

Michael, P., Superfesky, M., Uranoswki, L., 2010. Challenges of applying geomorphic and stream reclamation methodologies to mountaintop mining and excess spoil fill construction in steep slope topography (eg central appalachia), in: Proceedings, Joint Conference of the 27th Annual Meetings of the American Society of Mining and Reclamation, 12th Annual Pennsylvania Abandoned Mine Reclamation Conference, and 4th Annual Appalachian Regional Reforestation Initiative Mined Land Reforestation Conference, ASMR, Lexington. pp. 610–634.

Miller, A.J., Zégre, N., 2016. Landscape-scale disturbance: Insights into the complexity of catchment hydrology in the mountaintop removal mining region of the eastern united states. Land 5, 22.

Miller, A.J., Zégre, N.P., 2014. Mountaintop removal mining and catchment hydrology. Water 6, 472–499.

Morisawa, M.E., 1962. Quantitative geomorphology of some watersheds in the appalachian plateau. Geological Society of America Bulletin 73, 1025–1046.

Mukhopadhyay, S., Masto, R., Yadav, A., George, J., Ram, L., Shukla, S., 2016. Soil quality index for evaluation of reclaimed coal mine spoil. Science of the Total Environment 542, 540–550.

Negley, T.L., Eshleman, K.N., 2006. Comparison of stormflow responses of surface-mined and forested watersheds in the appalachian mountains, usa. Hydrological Processes: An International Journal 20, 3467–3483.

Nippgen, F., Ross, M.R., Bernhardt, E.S., McGlynn, B.L., 2017. Creating a more perennial problem? mountaintop removal coal mining enhances and sustains saline baseflows of appalachian watersheds. Environmental science & technology 51, 8324–8334.

Oliphant, A.J., Wynne, R., Zipper, C.E., Ford, W.M., Donovan, P., Li, J., 2017. Autumn olive (elaeagnus umbellata) presence and proliferation on former surface coal mines in eastern usa. Biological Invasions 19, 179–195.

Osterkamp, W., Hupp, C.R., Stoffel, M., 2012. The interactions between vegetation and erosion: new directions for research at the interface of ecology and geomorphology. Earth Surface Processes and Landforms 37, 23–36.

Outerbridge, W.F., 1987. The Logan plateau, a young physiographic region in West Virginia, Kentucky, Virginia, and Tennessee. Technical Report. USGPO,.

Palmer, M.A., Bernhardt, E.S., Schlesinger, W.H., Eshleman, K.N., Foufoula-Georgiou, E., Hendryx, M.S., Lemly, A.D., Likens, G.E., Loucks, O.L., Power, M.E., et al., 2010. Mountaintop mining consequences. Science 327, 148–149.

Parker, R.N., Hales, T.C., Mudd, S.M., Grieve, S.W., Constantine, J.A., 2016. Colluvium supply in humid regions limits the frequency of storm-triggered landslides. Scientific Reports 6, 1–7.

Patra, A.K., Gautam, S., Kumar, P., 2016. Emissions and human health impact of particulate matter from surface mining operation—a review. Environmental Technology & Innovation 5, 233–249.

Pelletier, J.D., Brad Murray, A., Pierce, J.L., Bierman, P.R., Breshears, D.D., Crosby, B.T., Ellis, M., Foufoula-Georgiou, E., Heimsath, A.M., Houser, C., et al., 2015. Forecasting the response of earth's surface to future climatic and land use changes: A review of methods and research needs. Earth's Future 3, 220–251.

Pericak, A.A., Thomas, C.J., Kroodsma, D.A., Wasson, M.F., Ross, M.R., 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, e0197758.

Phillips, J., 2016. Climate change and surface mining: A review of environment-human interactions & their spatial dynamics. Applied Geography 74, 95–108.

Phillips, J.D., 2004. Impacts of surface mine valley fills on headwater floods in eastern kentucky. Environmental Geology 45, 367–380.

Portenga, E.W., Bierman, P.R., Trodick, C.D., Greene, S.E., DeJong, B.D., Rood, D.H., Pavich, M.J., 2019. Erosion rates and sediment flux within the potomac river basin quantified over millennial timescales using beryllium isotopes. GSA Bulletin 131, 1295–1311.

Reed, M., Kite, S., 2020. Peripheral gully and landslide erosion on an extreme anthropogenic landscape produced by mountaintop removal coal mining. Earth Surface Processes and Landforms 45, 2078–2090.

Rengers, F.K., Tucker, G., Mahan, S., 2016. Episodic bedrock erosion by gully-head migration, colorado high plains, usa. Earth Surface Processes and Landforms 41, 1574–1582.

Rieke-Zapp, D., Nearing, M., 2005. Slope shape effects on erosion: a laboratory study. Soil Science Society of America Journal 69, 1463–1471.

Ritter, J.B., Gardner, T.W., 1993. Hydrologic evolution of drainage basins disturbed by surface mining, central pennsylvania. Geological Society of America Bulletin 105, 101–115.

Ross, M.R., 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, 2064–2074.

Ross, M.R., Nippgen, F., Hassett, B.A., McGlynn, B.L., Bernhardt, E.S., 2018. Pyrite oxidation drives exceptionally high weathering rates and geologic co2 release in mountaintop-mined landscapes. Global Biogeochemical Cycles 32, 1182–1194.

Ross, M.R., Nippgen, F., McGlynn, B.L., Thomas, C.J., Brooks, A.C., Shriver, R.K., Moore, E.M., Bernhardt, E.S., 2021. Mountaintop mining legacies constrain ecological, hydrological and biogeochemical recovery trajectories. Environmental Research Letters 16, 075004.

Russell, H., 2012. Soil and slope stability study of geomorphic landform profiles versus approximate original contour for valley fill designs .

Salam, S., Xiao, M., Evans, J.C., 2020. Strain history and short-period aging effects on the strength and cyclic response of fine-grained coal refuse. Journal of Geotechnical and Geoenvironmental Engineering 146, 04020113.

Salam, S., Xiao, M., Khosravifar, A., Liew, M., Liu, S., Rostami, J., 2019. Characterization of static and dynamic geotechnical properties and behaviors of fine coal refuse. Canadian Geotechnical Journal 56, 1901–1916.

Schmid, M., Ehlers, T.A., Werner, C., Hickler, T., Fuentes-Espoz, J.P., 2018. Effect of changing vegetation and precipitation on denudation–part 2: Predicted landscape response to transient climate and vegetation cover over millennial to million-year timescales. Earth Surface Dynamics 6, 859–881.

Schmidt, K., Roering, J., Stock, J., Dietrich, W., Montgomery, D., Schaub, T., 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the oregon coast range. Canadian Geotechnical Journal 38, 995–1024.

Schor, H.J., Gray, D.H., 2007. Landforming: an environmental approach to hillside development, mine reclamation and watershed restoration. John Wiley & Sons.

Schulz, K.J., DeYoung, J.H., Seal, R.R., Bradley, D.C., 2017. Critical mineral resources of the United States: economic and environmental geology and prospects for future supply.

Schwanghart, W., Groom, G., Kuhn, N.J., Heckrath, G., 2013. Flow network derivation from a high resolution dem in a low relief, agrarian landscape. Earth Surface Processes and Landforms 38, 1576–1586.

Schwanghart, W., Scherler, D., 2014. Topotoolbox 2–matlab-based software for topographic analysis and modeling in earth surface sciences. Earth Surface Dynamics 2, 1–7.

Sears, A., Hopkinson, L., Quaranta, J., 2020. Predicting erosion at valley fills with two reclamation techniques in mountainous terrain. International Journal of Mining, Reclamation and Environment 34, 223–237.

Sena, K., Franklin, J.A., Swab, R.M., Hall, S.L., 2021. Plant communities on appalachian mined lands. Appalachia's Coal-Mined Landscapes: Resources and Communities in a New Energy Era , 111–134.

Sharma, H., Ehlers, T.A., 2022. Effects of seasonal variations in vegetation and precipitation on catchment erosion rates along a climate and ecological gradient: Insights from numerical modelling. Earth Surface Dynamics Discussions , 1–22.

Sharma, H., Ehlers, T.A., Glotzbach, C., Schmid, M., Tielbörger, K., 2021. Effect of rock uplift and milankovitch timescale variations in precipitation and vegetation cover on catchment erosion rates. Earth Surface Dynamics 9, 1045–1072.

Sharma, R.S., Gong, M., Azadi, S., Gans, A., Gondret, P., Sauret, A., 2022. Erosion of cohesive grains by an impinging turbulent jet. Physical Review Fluids 7, 074303.

Sharmeen, S., Willgoose, G.R., 2007. A one-dimensional model for simulating armouring and erosion on hillslopes: 2. long term erosion and armouring predictions for two contrasting mine spoils. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group 32, 1437–1453.

Shi, W., Wang, J., Li, X., Xu, Q., Jiang, X., 2021. Multi-fractal characteristics of reconstructed landform and its relationship with soil erosion at a large opencast coal-mine in the loess area of china. Geomorphology 390, 107859.

Shields, A., 1936. Application of similarity principles and turbulence research to bed-load movement .

Shobe, C., 2023. Code and data for "The uncertain future of mountaintop-removal-mined landscapes 1: How mining changes erosion processes and variables" doi:10.5281/zenodo.10059513.

Shobe, C.M., 2022. How impervious are solar arrays? on the need for geomorphic assessment of energy transition technologies. Earth Surface Processes and Landforms 47, 3219–3223.

Shobe, C.M., Tucker, G.E., Barnhart, K.R., 2017. The SPACE 1.0 model: a landlab component for 2-d calculation of sediment transport, bedrock erosion, and landscape evolution. Geoscientific Model Development 10, 4577–4604.

Shobe, C.M., Turowski, J.M., Nativ, R., Glade, R.C., Bennett, G.L., Dini, B., 2021. The role of infrequently mobile boulders in modulating landscape evolution and geomorphic hazards. Earth-Science Reviews 220, 103717.

Shrestha, R.K., Lal, R., 2008. Land use impacts on physical properties of 28 years old reclaimed mine soils in ohio. Plant and soil 306, 249–260.

Shrestha, R.K., Lal, R., 2010. Carbon and nitrogen pools in reclaimed land under forest and pasture ecosystems in ohio, usa. Geoderma 157, 196–205.

Simon, A., Collison, A.J., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth surface processes and landforms 27, 527–546.

Skousen, J., Daniels, W.L., Zipper, C.E., 2021. Soils on appalachian coal-mined lands. Appalachia's Coal-Mined Landscapes: Resources and Communities in a New Energy Era , 85–109.

Skousen, J., Zipper, C.E., 2014. Post-mining policies and practices in the eastern usa coal region. International journal of coal science & technology 1, 135–151.

Skousen, J., Zipper, C.E., 2021. Coal mining and reclamation in appalachia, in: Appalachia's Coal-Mined Landscapes. Springer, pp. 55–83.

Sonter, L.J., Ali, S.H., Watson, J.E., 2018. Mining and biodiversity: key issues and research needs in conservation science. Proceedings of the Royal Society B 285, 20181926.

Sonter, L.J., Maron, M., Bull, J.W., Giljum, S., Luckeneder, S., Maus, V., McDonald-Madden, E., Northey, S.A., Sánchez, L.E., Valenta, R., et al., 2023. How to fuel an energy transition with ecologically responsible mining. Proceedings of the National Academy of Sciences 120, e2307006120.

Sovacool, B.K., Ali, S.H., Bazilian, M., Radley, B., Nemery, B., Okatz, J., Mulvaney, D., 2020. Sustainable minerals and metals for a low-carbon future. Science 367, 30–33.

Spotila, J.A., Prince, P.S., 2022. Geomorphic complexity and the case for topographic rejuvenation of the appalachian mountains. Geomorphology , 108449.

Tang, L., Werner, T.T., 2023. Global mining footprint mapped from high-resolution satellite imagery. Communications Earth & Environment 4, 134.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water resources research 33, 309–319.

Temme, A.J., Vanwalleghem, T., 2016. Lorica–a new model for linking landscape and soil profile evolution: Development and sensitivity analysis. Computers & Geosciences 90, 131–143.

Thomas, C.J., Shriver, R.K., Nippgen, F., Hepler, M., Ross, M.R., 2022. Mines to forests? analyzing long-term recovery trends for surface coal mines in central appalachia. Restoration Ecology , e13827.

Topp, W., Thelen, K., Kappes, H., 2010. Soil dumping techniques and afforestation drive ground-dwelling beetle assemblages in a 25-year-old opencast mining reclamation area. Ecological Engineering 36, 751–756.

Toy, T.J., Black, J.P., 2000. Topographic reconstruction: the theory and practice. Reclamation of drastically disturbed lands 41, 41–75.

Tucker, G.E., 2009. Natural experiments in landscape evolution. Earth Surface Processes and Landforms 34, 1450–1460.

Tucker, G.E., Hancock, G.R., 2010. Modelling landscape evolution. Earth Surface Processes and Landforms 35, 28–50.

Vidal, O., Goffé, B., Arndt, N., 2013. Metals for a low-carbon society. Nature Geoscience 6, 894–896.

Vidal-Macua, J.J., Nicolau, J.M., Vicente, E., Moreno-de Las Heras, M., 2020. Assessing vegetation recovery in reclaimed opencast mines of the teruel coalfield (spain) using landsat time series and boosted regression trees. Science of the Total Environment 717, 137250.

Wali, M.K., 1999. Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. Plant and soil 213, 195–220.

Wang, J., Guo, L., Bai, Z., Yang, L., 2016. Using computed tomography (ct) images and multi-fractal theory to quantify the pore distribution of reconstructed soils during ecological restoration in opencast coal-mine. Ecological engineering 92, 148–157.

Welivitiya, W.D.P., Willgoose, G.R., Hancock, G.R., 2021. Evaluating a new landform evolution model: a case study using a proposed mine rehabilitation landform. Earth Surface Processes and Landforms 46, 2298–2314.

Werner, C., Schmid, M., Ehlers, T.A., Fuentes-Espoz, J.P., Steinkamp, J., Forrest, M., Liakka, J., Maldonado, A., Hickler, T., 2018. Effect of changing vegetation and precipitation on denudation–part 1: Predicted vegetation composition and cover over the last 21 thousand years along the coastal cordillera of chile. Earth Surface Dynamics 6, 829–858.

Whipple, K., Forte, A., DiBiase, R., Gasparini, N., Ouimet, W., 2017. Timescales of landscape response to divide migration and drainage capture: Implications for the role of divide mobility in landscape evolution. Journal of Geophysical Research: Earth Surface 122, 248–273.

Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research: Solid Earth 104, 17661–17674.

Wickham, J., Wood, P.B., Nicholson, M.C., Jenkins, W., Druckenbrod, D., Suter, G.W., Strager, M.P., Mazzarella, C., Galloway, W., Amos, J., 2013. The overlooked terrestrial impacts of mountaintop mining. BioScience 63, 335–348.

Wickham, J.D., Riitters, K.H., Wade, T., Coan, M., Homer, C., 2007. The effect of appalachian mountaintop mining on interior forest. Landscape ecology 22, 179–187.

Wiley, J.B., 2001. Reconnaissance of stream geomorphology, low streamflow, and stream temperature in the mountaintop coal-mining region, southern West Virginia, 1999-2000. volume 1. US Department of the Interior, US Geological Survey.

Wilkinson, B.H., 2005. Humans as geologic agents: A deep-time perspective. Geology 33, 161–164.

Willgoose, G., Bras, R.L., Rodriguez-Iturbe, I., 1991. A coupled channel network growth and hillslope evolution model: 1. theory. Water Resources Research 27, 1671–1684.

Willgoose, G., Riley, S., 1998. The long-term stability of engineered landforms of the ranger uranium mine, northern territory, australia: application of a catchment evolution model. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group 23, 237–259.

Wohl, E., Brierley, G., Cadol, D., Coulthard, T.J., Covino, T., Fryirs, K.A., Grant, G., Hilton, R.G., Lane, S.N., Magilligan, F.J., et al., 2019. Connectivity as an emergent property of geomorphic systems. Earth Surface Processes and Landforms 44, 4–26.

Xiang, J., Chen, J., Sofia, G., Tian, Y., Tarolli, P., 2018. Open-pit mine geomorphic changes analysis using multi-temporal uav survey. Environmental earth sciences 77, 1–18.

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, 337–349.

Zipper, C.E., Burger, J.A., Skousen, J.G., Angel, P.N., Barton, C.D., Davis, V., Franklin, J.A., 2011. Restoring forests and associated ecosystem services on appalachian coal surface mines. Environmental management 47, 751–765.

Zipper, C.E., Daniels, W.L., Bell, J.C., 1989. The practice of "approximate original contour" in the central appalachians. ii. economic and environmental consequences of an alternative. Landscape and urban planning 18, 139–152.

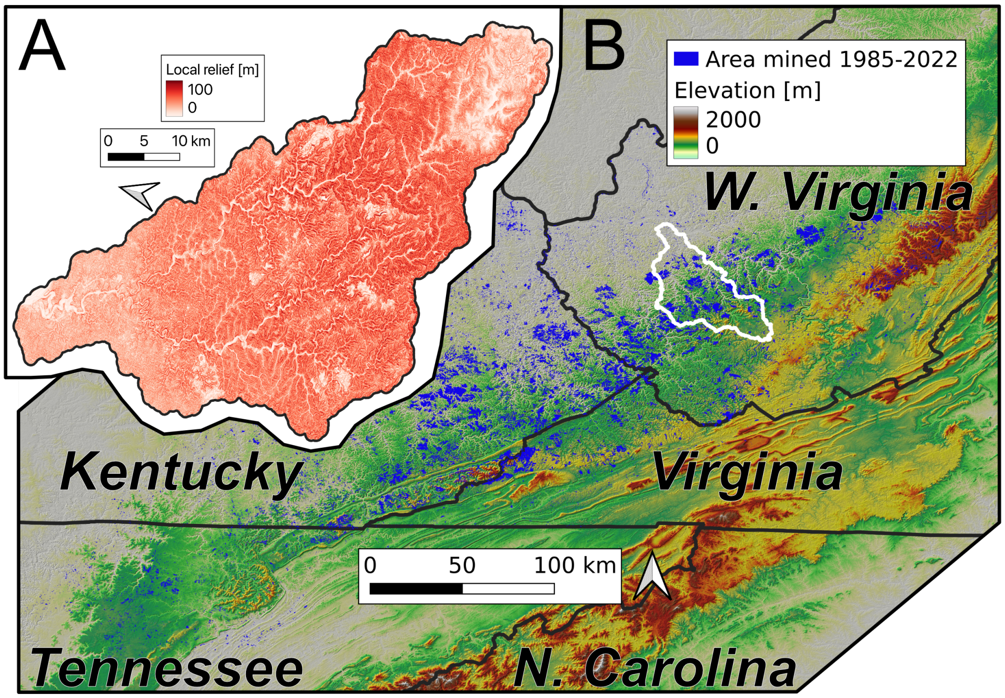

Figure 1: The AC region is characterized by steep-sided river valleys incised into the Appalachian Plateau. A) zoom-in of white polygon—the Coal River watershed—colored by local relief in a 150 m wide moving window and rotated for fit. B) Shaded relief map of the AC region colored by elevation. Blue 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. Elevation data is from the U.S. Geological Survey National Elevation Dataset.

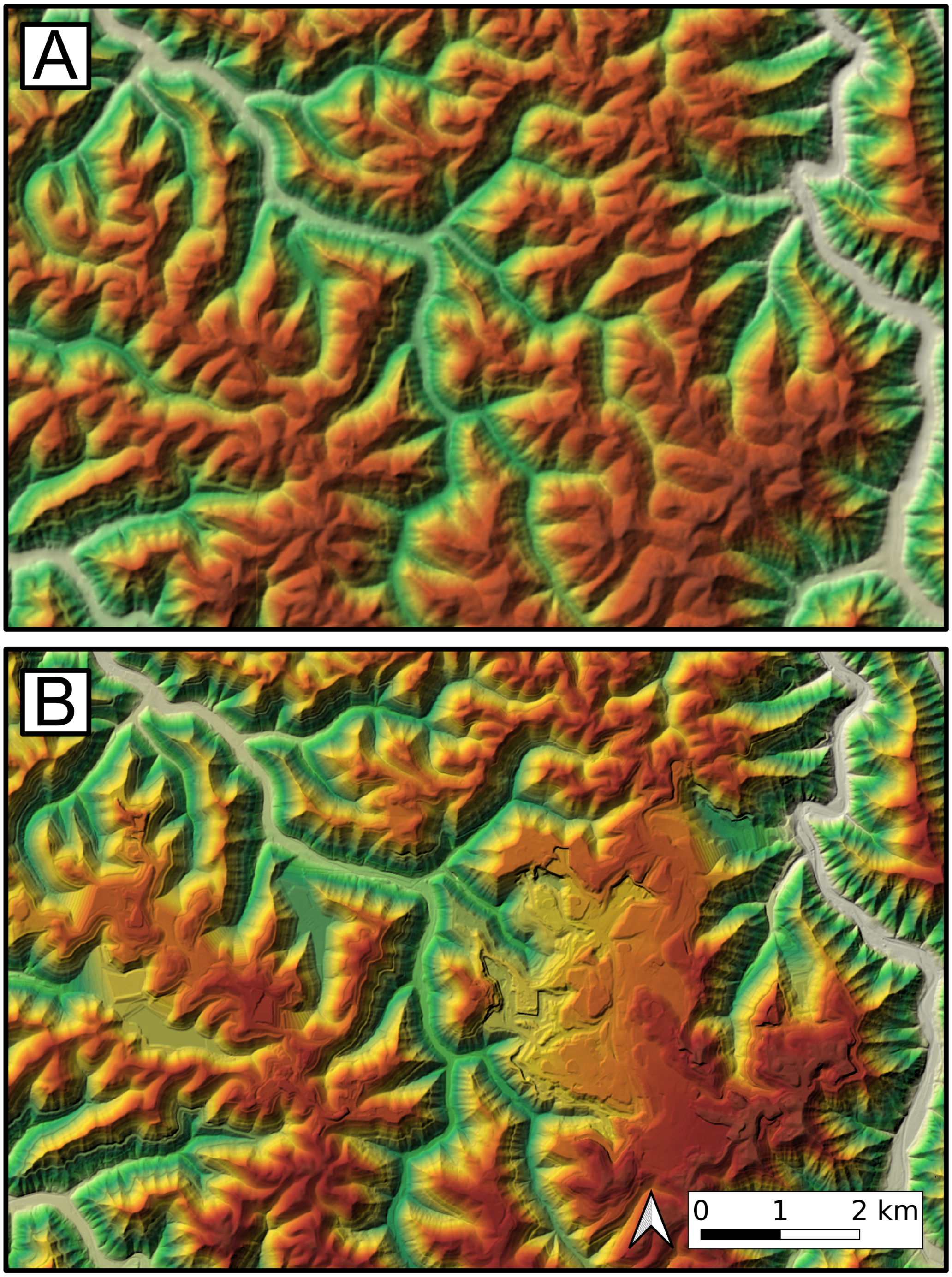

Figure 2: A typical view of the AC landscape before (A) and after (B) extensive MTR/VF mining. The primary morphologic effects of MTR/VF are the flattening and expansion of ridgetops and the filling of headwater streams. DEMs were produced by Ross et al. (2016); total relief in this image is approximately 400 m.

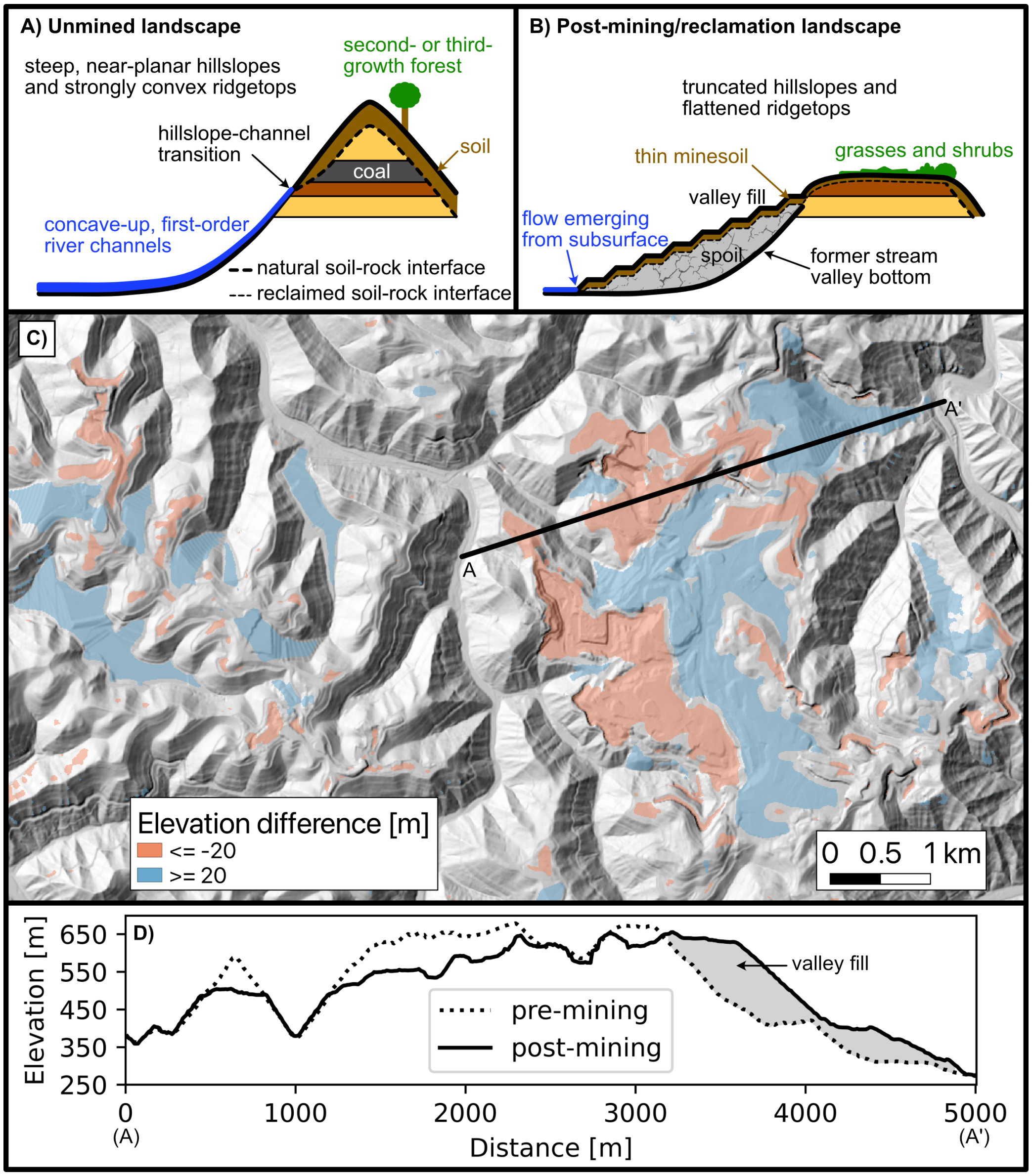

Figure 3: A) and B) Representative schematic cross-sections of unmined and mined/reclaimed landscapes, respectively. C) Lidar-derived DEM of an intensively mined area, with elevation differences between the post-mining and pre-mining topography shown in color overlays. Red areas indicate reduced elevation 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.

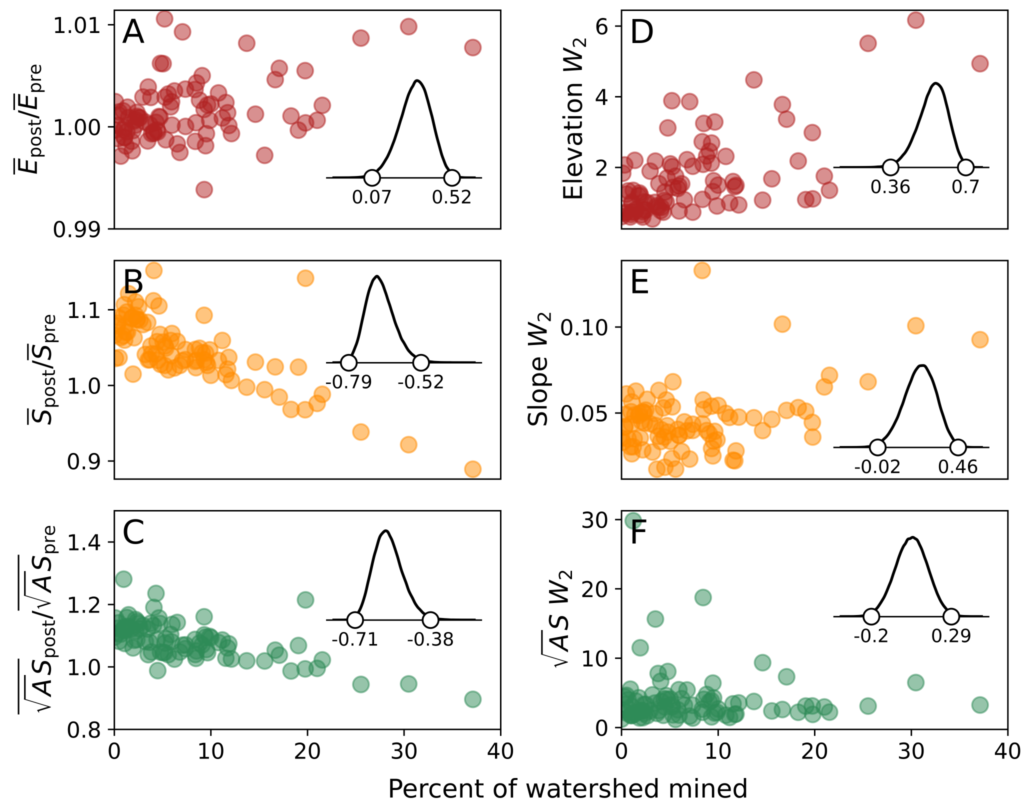

Figure 4: Comparisons between pre- and post-mining geomorphic characteristics of 88 HUC-12 watersheds with at least 90% coverage of pre- and post-mining elevation data. A–C show the influence of mining on the ratio of post- to pre-mining mean elevation, mean slope, and mean area–slope product, respectively. 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.

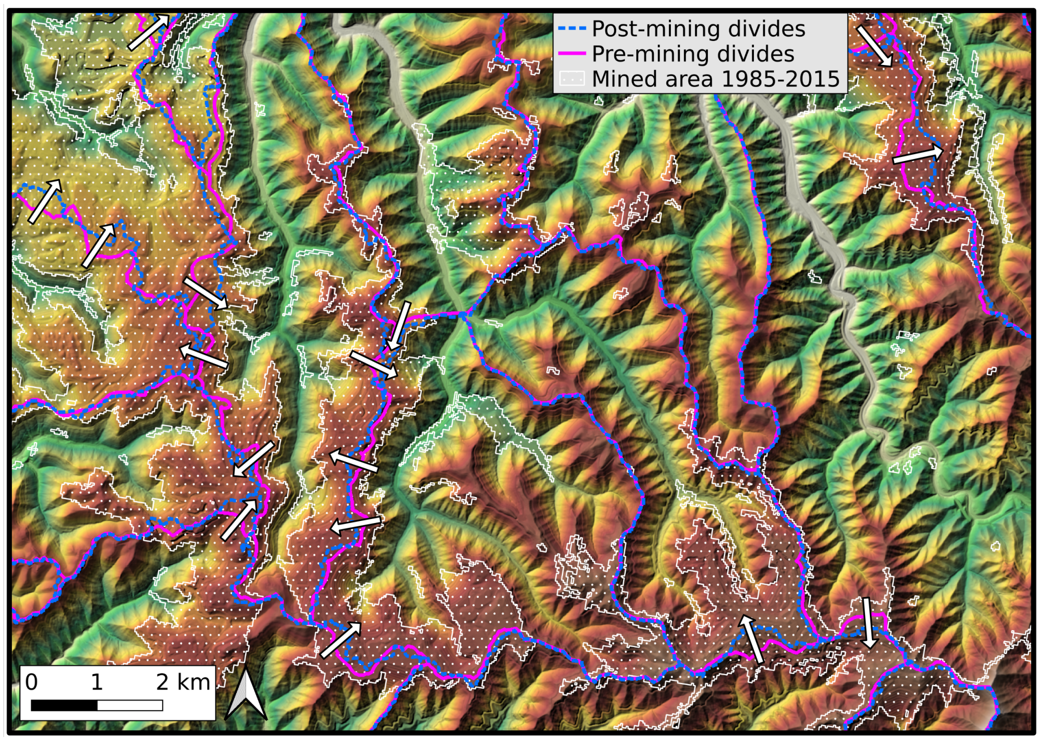

Figure 5: Mining-induced drainage divide reorganization. Drainage divides mapped from pre-mining and post-mining DEMs (pink solid line and blue dashed line, respectively) using TopoToolbox 2 (Schwanghart and Scherler, 2014). Divides have not moved in places that have not experienced mining. Mined areas (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).

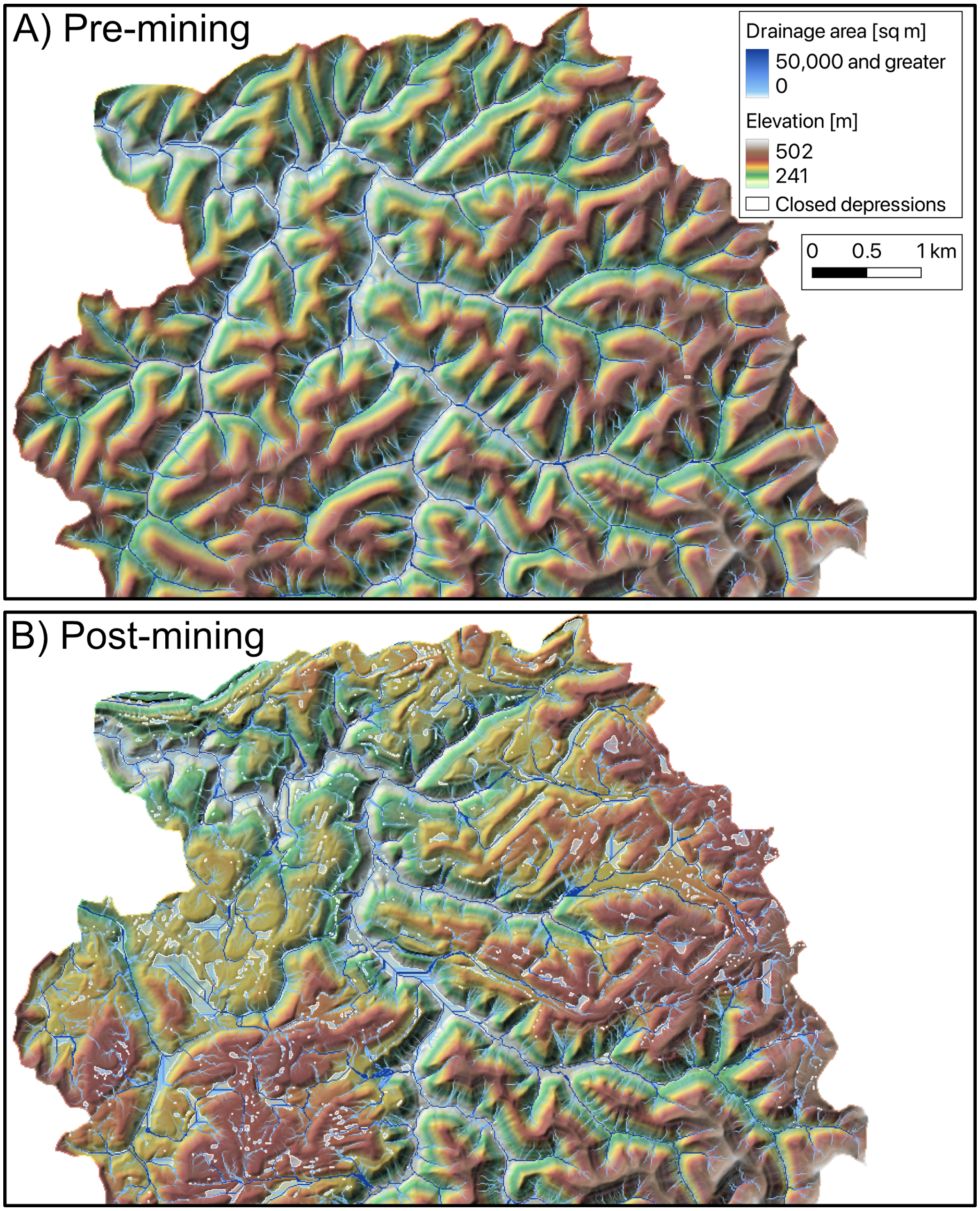

Figure 6: Differences in flow routing and accumulation across the pre-mining (A) and post-mining (B) landscapes of the Mud River, WV using D∞ routing (Tarboton, 1997; Barnes, 2017). Mining rearranges catchment areas at multiple scales and creates broad, flat regions that host many large closed depressions.

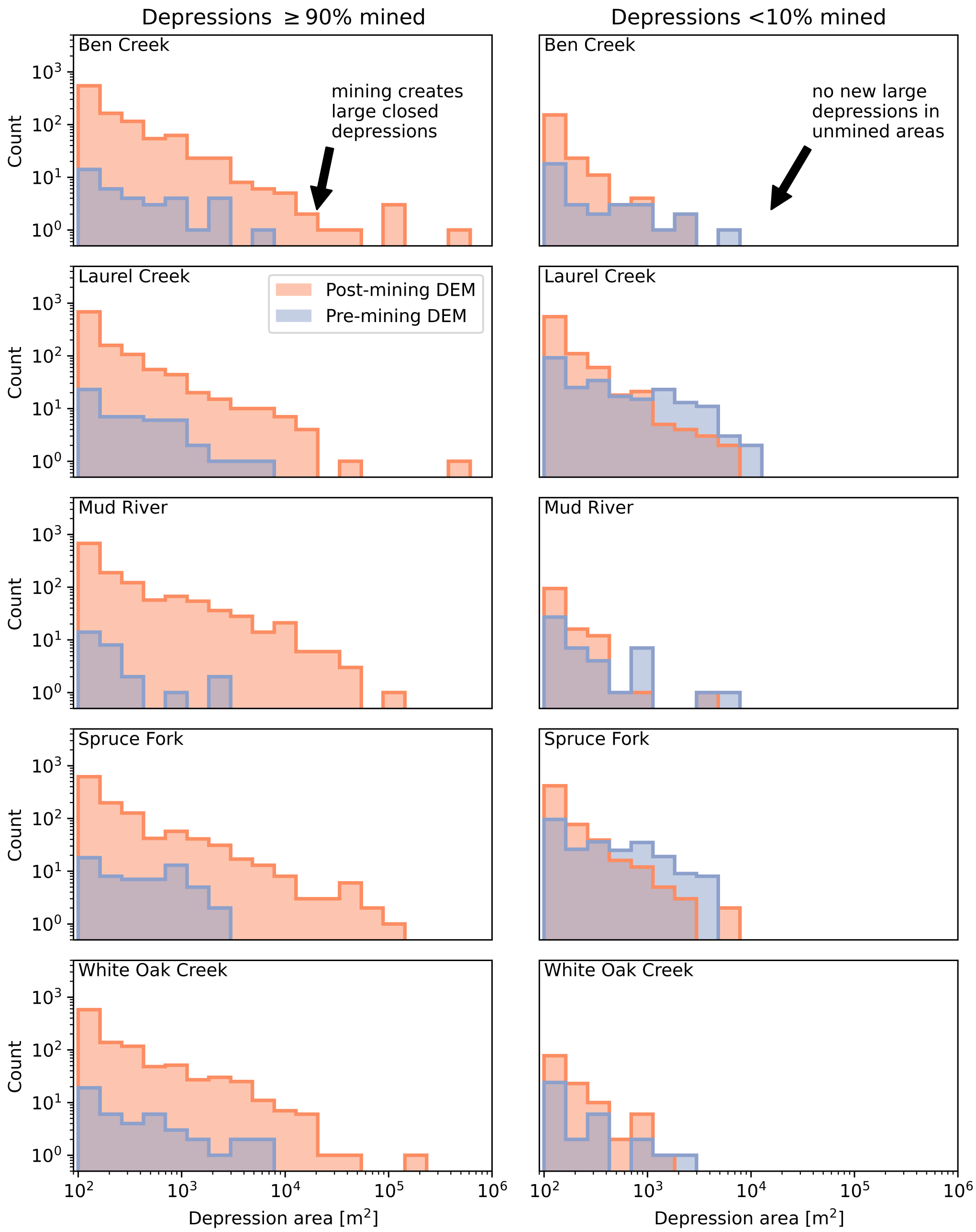

Figure 7: Histograms of closed depressions in pre- (blue) and post-mining (orange) DEMs for five HUC-12 river basins. Depressions with mean elevations below the 20$^{\text{th}}$ percentile of pre-mine elevation in each basin are excluded to avoid counting spurious depressions identified in river valleys (Fig. 6). Separating depressions by the extent to which they overlap mined areas (Pericak et al., 2018) shows that heavily mined areas are more likely to host large ($> 10^4$ m^2) closed depressions due to the reshaping of the land surface. This is not observed in unmined areas, indicating that their formation in mined areas is not an artefact of differences between the two DEMs.

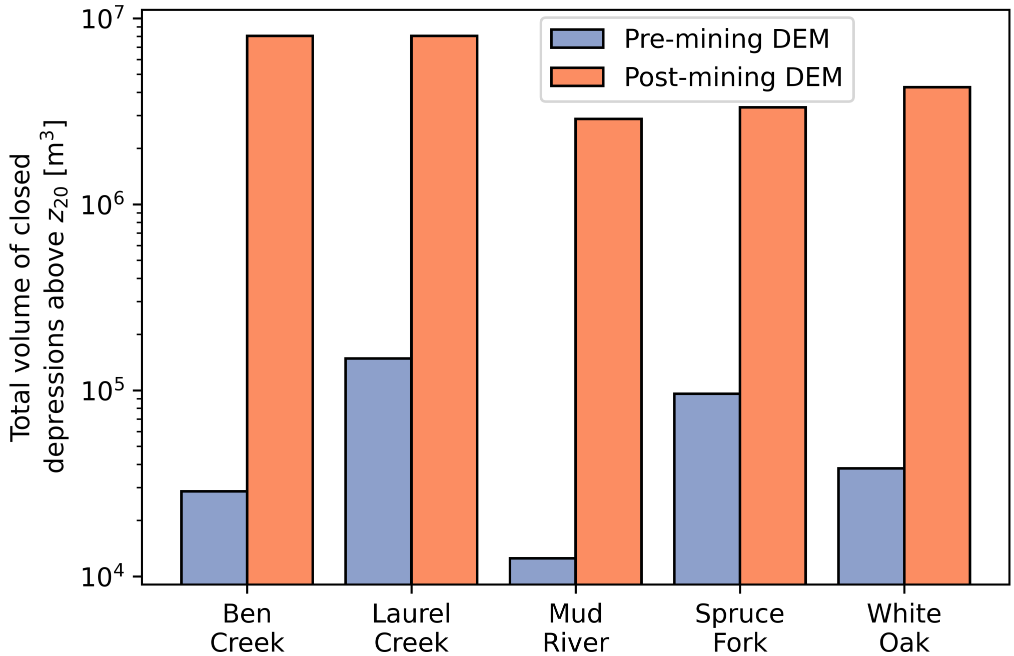

Figure 8: Total volume of closed depressions in five watersheds before and after MTR/VF mining. Depressions with mean elevations below the 20$^{\text{th}}$ percentile of pre-mining elevation (the z_{20}) are excluded to avoid counting spurious depressions in river valleys. Note the logarithmic y-axis scale; MTR/VF mining increases closed depression volume by well over an order of magnitude in all cases, and in some cases by several orders of magnitude.

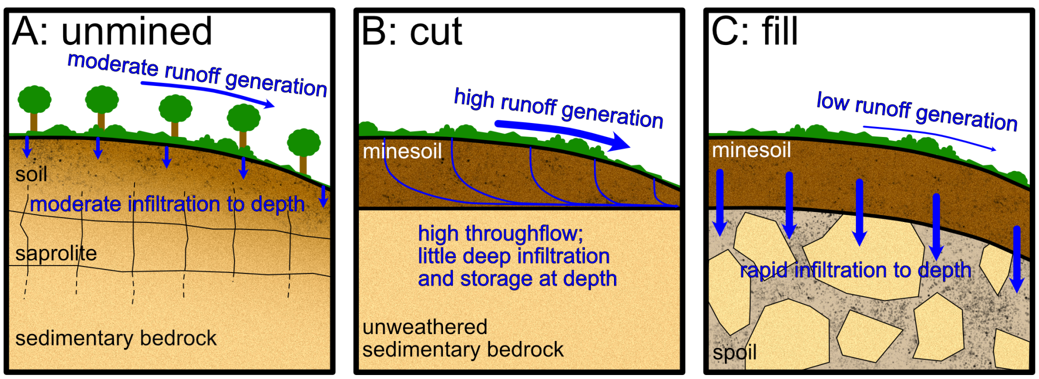

Figure 9: Schematic demonstrating differences in surface water balance among unmined (A), cut (B), and filled (C) portions of the lanscape. Differences in subsurface properties influence the relative efficiency of runoff generation. Cut portions of the landscape generate more runoff per unit rainfall than unmined land, whereas filled portions generate less runoff than unmined land.

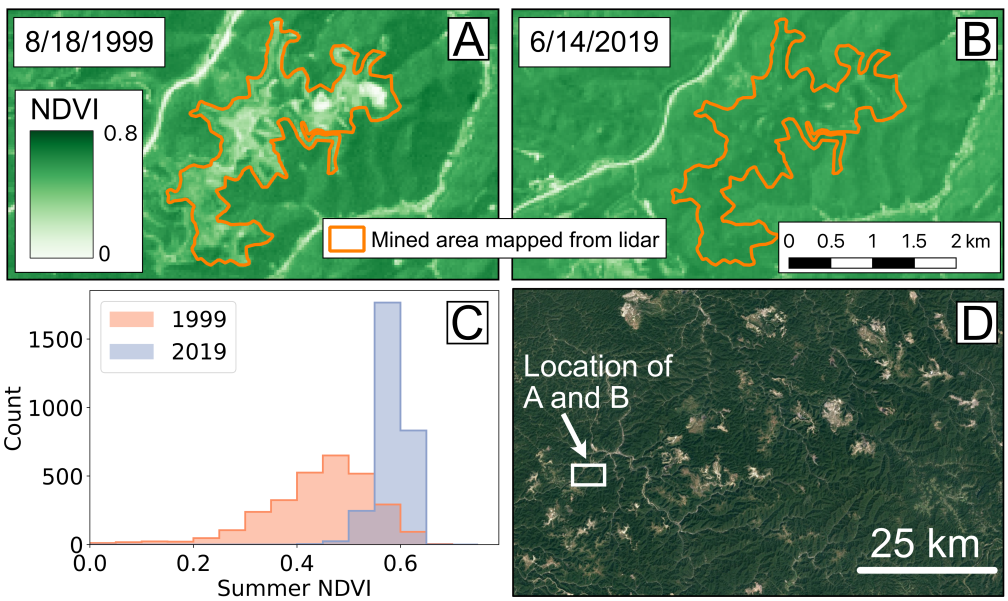

Figure 10: A demonstration of the influence of MTR/VF mining on vegetation loss and recovery. A) In this Landsat image, the normalized difference vegetation index (NDVI; a spectral measure of greenness) is lower within the mined polygon (mapped by Reed and Kite (2020)) than in the surrounding forest, indicating that mining has reduced vegetation cover. B) 20 years later, NDVI is similar between the mined polygon and its surroundings. C) The distribution of NDVI within the mined polygon has shifted towards higher values and become narrower over the 20-year period. D) Zooming out illustrates the striking differences in vegetation cover between active mines and the surrounding landscape.

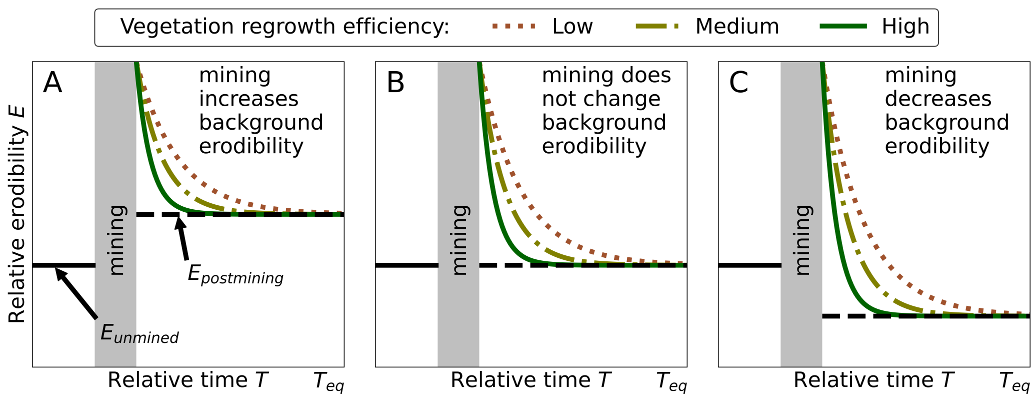

Figure 11: Proposed scenarios for the potential effects of material property changes on erodibility of mined landscapes under different vegetation regrowth efficiencies. Solid black lines show pre-mining erodibility E_{unmined}. Once mining occurs (grey boxes), landscapes experience increased erodibility 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. Line color and style indicate different vegetation regrowth efficiencies, which set the time T_{eq} that it takes to reach the new minimum erodibility.