Field and LiDAR data observations of erosion on anthropogenic valley fills and associated landscape produced by mountaintop removal/valley fill coal mining in Central Appalachia

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Abstract

Mountaintop removal/valley fill coal mining (MTR/VF) in Central Appalachia has buried an estimated 4000 km of headwater streams, but the geomorphic implications of the constructed anthropogenic valley fills and associated mined landscape have been studied very little. This landscape requires no maintenance in perpetuity once reclamation is considered to be complete. The first ever field-based study of erosional landforms on this type of mined landscape allowed for the subsequent classification of gullies and landslides within nine regional LiDAR datasets in a transect from eastern Kentucky to central West Virginia. Field observations indicate that gullies are associated with the overtopping of or intentional discharge from drainage systems. Nine-hundred ninety-one manually identified gullies were observed on 375 km^2 of mined landscape covered by the LiDAR datasets. Gullies were predominantly associated with the perimeter of the mined landscape, and the perimeter explained much of the variance within the number of gullies (R^2 = 0.72). Landslides were more abundant by a factor of

13 in a Kentucky dataset examined for landslides occurring along the perimeter of the mined landscape when compared to a West Virginia dataset. In all nine datasets, 21 landslides were observed within fully reclaimed valley fills, which was previously undocumented phenomenon. Previously measured regional differences in the angle of friction of mining spoils may explain the abundance of gullies and landslides in eastern Kentucky relative to West Virginia. Observations of erosion on the regional extensive MTR/VF landscape warrant further field and modeling studies to better ascertain future impacts.

Keywords: Anthropogenic geomorphology, gully erosion, coal mining, Appalachian, and LiDAR

Introduction

Humans are the primary geomorphic agents on the planet (Hooke, 1999; Walling, 2006). Surface mining is a potent expression of this extraordinary geomorphic work rate (Tarolli & Sofia, 2016). Mountaintop removal/valley fill coal mining (MTR/VF) is a controversial surface mining technique in which thick layers of bedrock are blasted apart and hauled away to extract interbedded and underlying coal (Miller & Zégre, 2014). MTR/VF has driven land-use change over the past several decades in the unglaciated Appalachian Plateaus of Central Appalachia and is uniquely practiced there (Townsend et al., 2009). The damaging environmental impacts of headwater stream burial from dumping mining spoils (unconsolidated waste rock) into steep, low-order valleys has been extensively documented in studies of downstream water chemistry and aquatic ecosystems (Griffith et al., 2012; Pond et al., 2008; Bernhardt & Palmer, 2011). The geomorphic processes operating upon MTR/VF landscapes that could exacerbate or ameliorate existing environmental problems have yet to be determined (Jaeger, 2015).

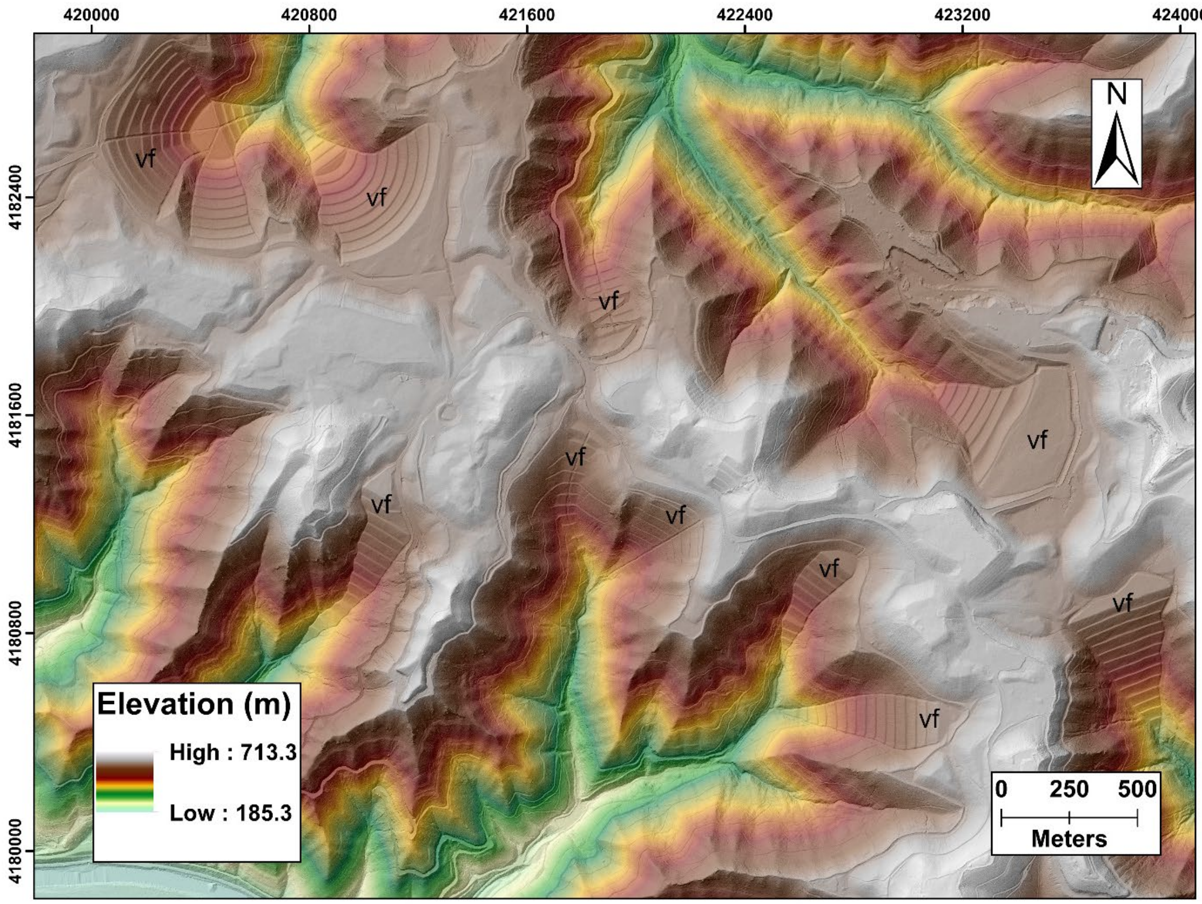

Figure 1. LiDAR-derived hillshade near Amherstdale, West Virginia, showing flat areas higher elevations and filled headwater valleys associated with the reclamation of MTR/VF. Ten valley fills are shown in the image and are marked with a "vf". The relief of the largest valley fill (NW corner) is over 200 m. Coordinates are Universal Transverse Mercator 17N.

The Surface Mining Control and Reclamation Act of 1977 (SMCRA) was introduced in the United States to minimize environmental damage associated with the haphazard storage of excess mining spoils and to assure mining sites were reclaimed to a form that resembles natural topography, approximate original contour (AOC) wherever feasible (Bell et al., 1989). The rugged topography of Central Appalachia motivated a geographically restricted variance to AOC under SMCRA (Zipper et al., 1989), which allows for area mining of mountaintops and the construction of valley fills (Fig. 1). Valley fills are anthropogenic landforms created when excess unconsolidated materials generated by mining are placed into headwater valleys adjacent to mined areas. The composition of a valley fill is largely an open framework of boulders at depth near the buried headwater valley (Greer et al., 2017), a finer-grained, stockpiled soil or soil-substitute at the surface, and a poorly sorted mix of coarse rock fragments and sand, which forms the bulk of the mass (Haering et al., 2004; Daniels & Zipper, 2010). Figure 2 provides the names of the landform elements that compose valley fills. The geometric design exhibited by valley fills is common among reclaimed mining landforms worldwide (Martin-Duque et al., 2010). Valley fills sampled in a United States Office of Surface Mining (OSM) study ranged in length from 90 to 3000 m and in volume from 0.15 to 152 million m^3 (OSM, 2002). There were ~7000 valley fills in the coalfields of southern West Virginia, eastern Kentucky, southwestern Virginia and north-central Tennessee as of 2001, which have buried an estimated 4000 km of headwater streams (Environmental Protection Agency (EPA), 2011). In a study that covered around a quarter of region affected by MTR/VF, Ross et al. (2016) estimated the volume of sediment composing the 1544 West Virginia valley fills in their study to be ~6.4 km^3. Valley fills are predominantly constructed with the “durable rock method” in which excess mining spoils deemed 80% durable rock (i.e., will not degrade into fine particles) is dumped into a headwater stream valley and is segregated by particle size through downslope grain flow (OSM, 2002). The dumped materials are graded into ~0.5 m m^{-1} outslopes with intervening slope-length-limiting terraces (Fig. 2) and armored by heavily compacted surface layer (Schor & Gray, 2007).

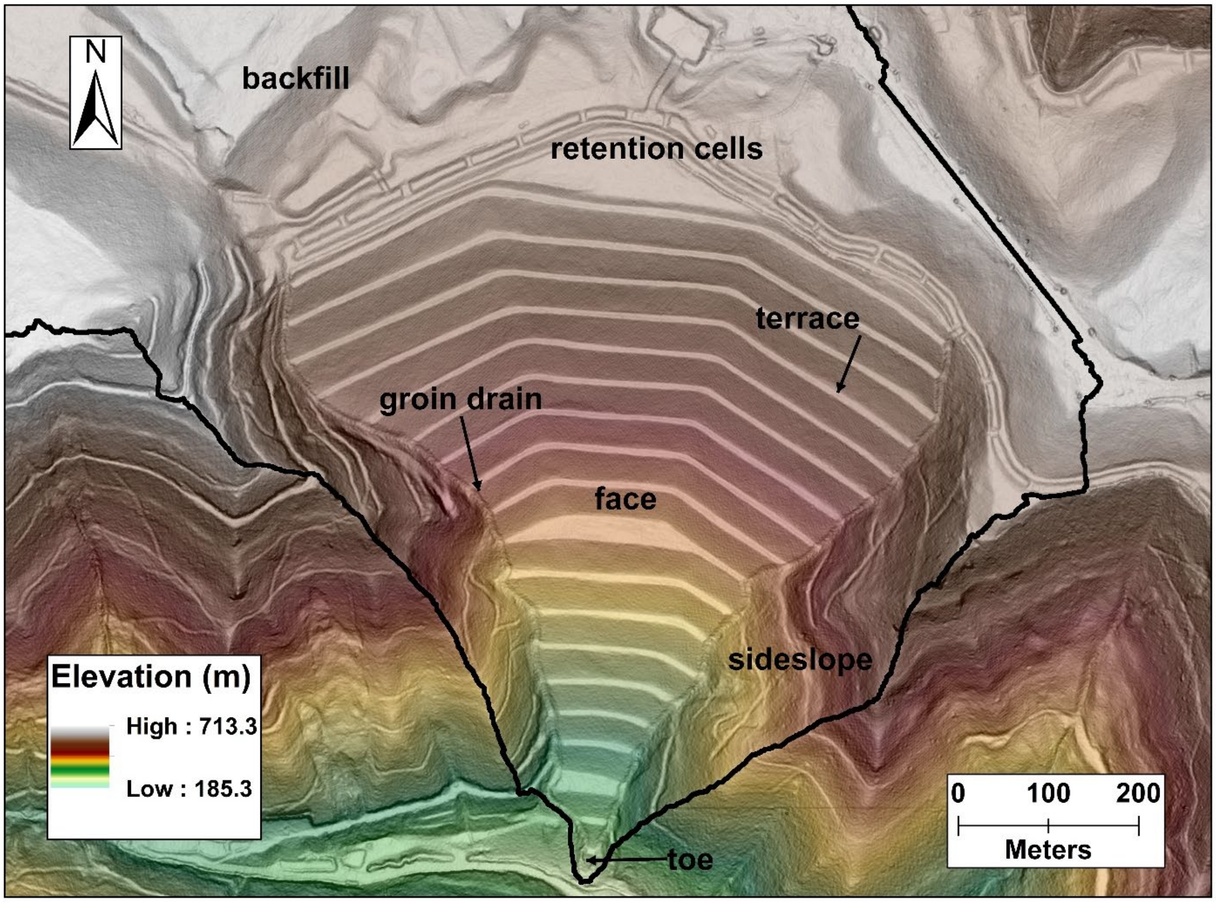

Figure 2. LiDAR-derived slopeshade of an anthropogenic valley fill landform with labeled components. Slope-length-limiting terraces bevel the face of the valley fill. The toe is the last terrace-outslope pair. Most valley fills have steep, relatively undisturbed sideslopes. The drains of a valley fill can be located on the perimeter (groin drains) or in the center (West Virginia only). Retention cells attenuate storm runoff to the valley fill and ring the perimeter of the mined landscape.

Geomorphic field studies on MTR/VF affected areas have been limited by property access (Jaeger, 2015). Wiley et al. (2001) observed a higher percentage of sediment grains <2 mm in diameter and a lower median grain size in West Virginia streams with valley-filled headwaters compared to those without. Fox (2009) found enhanced bank erosion in streams with valley-filled headwaters using carbon isotopes as tracers. Downstream channel morphology in MTR/VR affected streams were seen to have more exposed bedrock, deeper channels, and more fine-grained sediments compared to unaffected streams in a study by Jaeger (2015). Maxwell and Strager (2013) showed a general lowering of hillslope gradients and more flat land on MTR/VF landscapes in southwestern West Virginia using a comparison of post-mining Light Detection and Ranging (LiDAR)-derived digital elevation models (DEMS) and pre-mining photogrammetric DEMs. In the OSM study (2002), 34% of sampled valley fills showed some signs of erosion, such as gullies and seeps. Once valley fills have met the regulatory reclamation requirements, no further maintenance is required (OSM, 2002).

Surface mining drastically alters the hydrology of affected areas by changing both topography and surface materials (Osterkamp & Joseph, 2000; Miller & Zégre, 2016). Accelerated erosion has been associated with geometrically designed mining landforms due to enhanced sediment availability, surface-water rerouting, and flashy runoff from compacted surfaces (Schor & Gray, 2007; Martin-Duque et al. 2010). For example, Hancock et al. (2003) observed severe gully erosion on reclaimed uranium mines in Australia. Gully erosion appears to be a common phenomenon on other geometrically designed mine reclamation landscapes in varied climates (Haigh, 1992; Sanz et. al, 2008). The widespread observation of accelerated erosion on mining landforms has led some researchers to advocate geomorphic landform design, which seeks to create reclamation landscapes that more accurately mimic pre-existing hydrologic and geomorphic regimes (DePriest et al., 2015).

The aim of this study is to determine how valley fills are eroding at a process-level by studying the resultant landforms (Huggett, 2011). Gullies are posited to be a widespread landform on valley fills and wider MTR/VF landscape as gully erosion has been observed frequently on reclaimed mining landforms. For anthropogenic landscapes with little to no geomorphological literature about them and no natural analogs, observations stemming from exploratory field work is a vital first step in understanding what processes are possible. A field assessment of erosional landforms will lend credence to subsequent LiDAR-based remote sensing observations (Roering et al., 2013). The study represents the first attempt to study MTR/VF from a geomorphic perspective on reclaimed valley fills using field work and LiDAR data observations.

Field Study Areas and Background

The West Virginia Division of Natural Resources (WVDNR) acquired land in the southern West Virginia coalfields in 2016 to restore an elk (*Cervus canadensis*) population with the side effect of placing the land in the public domain. Two elk restoration sites with valley fills were chosen as field study areas: Copperas and Whitman (Fig. 3). Copperas is 17.5 km^2 and Whitman is 23.6 km^2. Combined, the field study areas contain 29 valley fills, with nine on Copperas and 20 on Whitman. The valley fills in the field study areas have either groin or center drains.

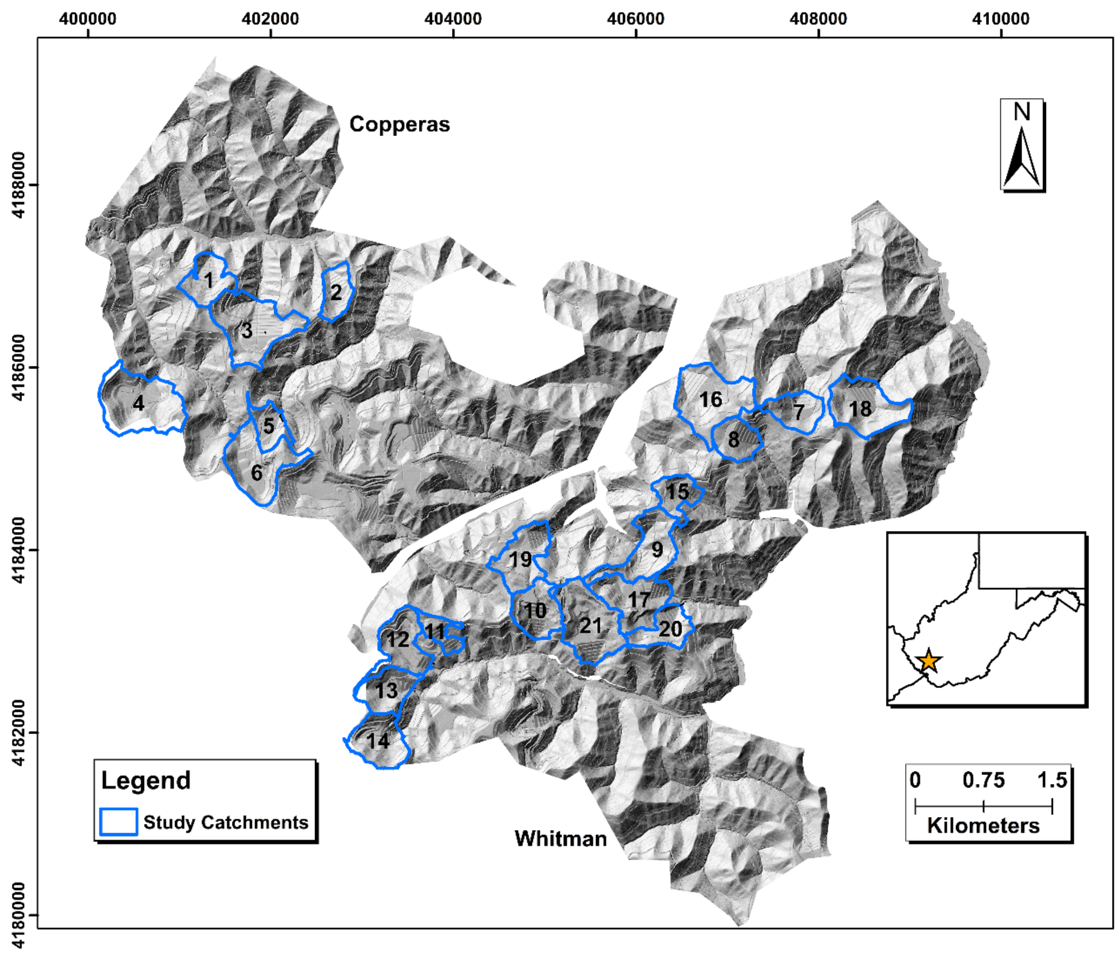

Figure 3. LiDAR-derived hillshade of field study ares with individual catchments outlined in blue. (inset) Location of field study areas in southwestern West Virginia.

The study areas are in the unglaciated Appalachian Plateaus physiographic province (Fenneman, 1938) in the proposed Logan Plateau physiographic region of Outerbridge (1987). The region is highly dissected by steep slopes with mean gradients of ~26° (Outerbridge, 1987). Hillslopes are generally covered in coarse colluvium derived from debris flows and other mass wasting events (Outerbridge, 1987). Debris flows occurring during high magnitude rainfall events are the primary evacuator of colluvial sediment in unchanneled hollows (Everett, 1979) much like other areas of Central and Southern Appalachia with steep topography (Cenderelli & Kite, 1998; Parker et al., 2016). No contemporary erosion rates for the area are available, but erosion rates measured elsewhere in the unglaciated Appalachian Plateaus range from an incision rate of 56.0-63.2 m Myr^{-1} in the Cheat River, West Virginia (Springer et al., 1997), to a ridge-lowering rate of 5.7 m Myr^{-1} on Pottsville sandstone located on the Allegheny Front in West Virginia (Hancock & Kirwan, 2007).

The geology of the study areas can be described as Middle Pennsylvanian interbedded sandstone, siltstone, limestone and coal, dipping slightly to the northeast (Greb et al., 2008). The ridges are or were in the case of MTR/VR affected areas capped by the basal portion of the Allegheny Formation with valleys and hillslopes underlain by Kanawha Formation. The Allegheny Formation contains thick feldspathic sandstones, shale and coal (Englund et al., 1986). The Kanawha Formation in southern West Virginia has been described by Martino (1996, pg. 1) as "lithic sandstone and mudrocks with subordinate coal and impure limestone" with both marine and non-marine facies. In Kentucky, the equivalent lithostratographic units are the Four Corners and Princess formations of the Breathitt Group (Huddle & England, 1966).

Methods

Field Work

Twenty-one valley-filled catchments within the field study areas were examined to assess the extent and types of erosional landforms (Fig. 3). The assessments were spatially focused on all components of the valley fills and the interfaces between sideslopes and valley fills (Fig. 2). The intent of the field work was to understand on-going erosional processes shaping valley fills and to provide context for subsequent

LiDAR data observations. Fifteen catchments in Whitman and six in Copperas were assessed (Supp. Table I). The approximate ages of valley fills were derived from a GIS database created by the West Virginia Department of Environmental Protection. An assessment would begin at the top of the catchment and proceed to the outlet stream beyond the toe by traversing along each terrace flat. LiDAR-derived slopeshades (slope raster with white-black colormap) of the catchments loaded onto a tablet computer served as guides to potential erosional features. If an erosional feature was encountered, dimensions were measured, and location was noted by GPS. A causal mechanism was sought for each encountered gully (e.g., runoff from a nearby road). Sideslopes were investigated if an erosional feature originating on the sideslope was seen to be interacting with the valley fill or was clearly visible on the LiDAR slopeshade.

LiDAR Data

High-resolution LiDAR data from the Southern coalfields of West Virginia and the Eastern coalfields of Kentucky were used throughout this study. The West Virginia data were obtained from the West Virginia Division of Natural Resources Technical Applications and GIS Unit (TAGIS) LiDAR repository (http://tagis.dep.wv.gov/data/lidar). The LiDAR data were flown during leaf-off conditions in October 2010. Field assessment showed the classified ground returns to have a median vertical accuracy of 0.141 m in open terrain and 0.188 m in brushy settings. The Kentucky LiDAR data were obtained from the Kentucky Geographic Network, KyGeoPortal (http://kygisserver.ky.gov/geoportal). The LiDAR data were flown by the state of Kentucky in the winter of 2011-2012. The Kentucky LiDAR data are georeferenced to the Kentucky Single Zone State Plane coordinate system, and have an average post spacing of 0.68 m. The stated vertical accuracy is 0.15 m.

LiDAR Data Observations

Along a transect of intensely mined areas from central West Virginia to eastern Kentucky, seven LiDAR datasets from West Virginia (Amherstdale, Birch River, Boone-Kanawha-Raleigh, Cannelton, Clay-Nicholas, Holden, and Wharton) and two LiDAR datasets from Kentucky (Floyd-Pike and Perry-Knott-Breathitt) were rendered at 1 m resolution to investigate if the erosional features seen in the field were widespread (Fig. 4). The Holden dataset includes the field study areas. Table I shows the total area of each dataset, the area affected by MTR/VF, and the percentage of land affected by MTR/VF. The perimeter of the mined landscape in each dataset was delineated manually on a LiDAR base, which allowed for the calculation of mined landscape area. Care was taken not to include land associated with legacy surface mining. Each dataset was manually examined using knowledge acquired in the field to assess the presence of erosional landforms. Landslides and gullies were of special interest, as geometrically designed mining reclamation landscapes have been observed to be prone to genesis of these landforms (Esling & Drake, 1988; Martin-Duque et al., 2010; Schor & Gray, 2007). The generation of these erosional feature datasets could serve future researchers should field access to MTR/VF become more common.

Table I. LiDAR datasets used for manual classification of gullies and landslides arranged from east to west (Fig. 4).

Dataset	Area (km^2)	MTR/VF (km^2)	MTR/VF (%)
Birch River, WV	81.72	23.14	28.31
Clay-Nicholas, WV	163.02	61.99	38.03
Cannelton, WV	79.47	22.52	28.33
Boone-Kanawha-Raleigh, WV	144.74	47.68	32.94
Wharton, WV	203.22	32.93	16.20
Amherstdale, WV	199.02	51.63	25.94
Holden, WV	181.08	33.04	18.24
Floyd-Pike, KY	178.84	32.06	17.93
Perry-Knott-Breathitt, KY	178.84	69.76	39.01

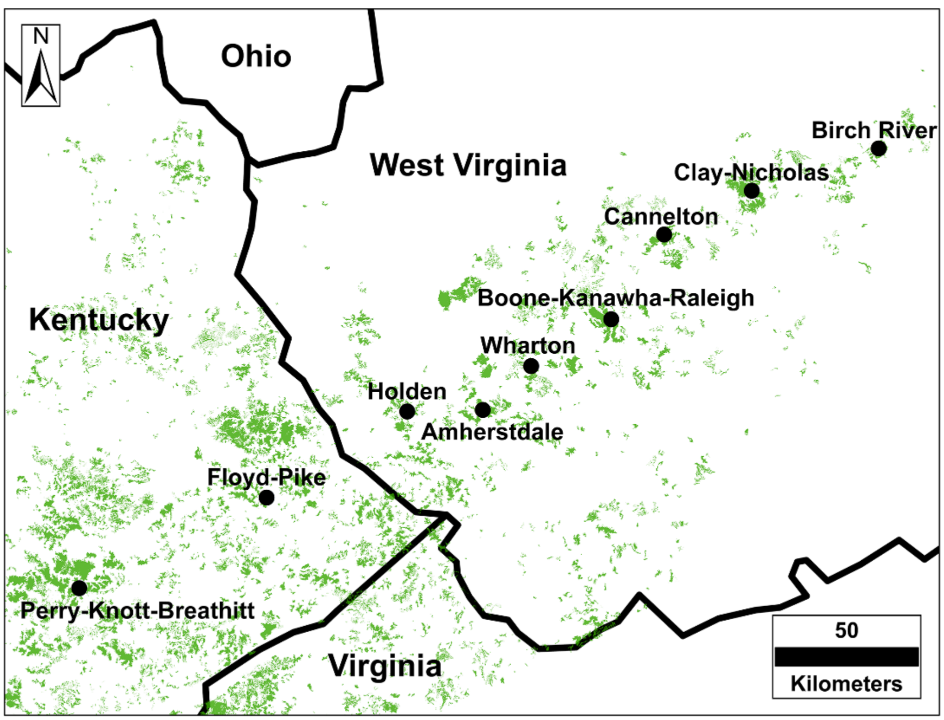

Figure 4. Location of LiDAR datasets used in manual classification of gullies and landslides. The green patches are the extent of MTR/VF.

Manual classification of gullies on MTR/VF was performed on the nine LiDAR datasets. Gullies are defined here as channels with steep sides and low width to depth ratios formed in unconsolidated materials due to land use change (Bull & Kirkby, 1997;

Poesen et al. 2003). Manual classification using airborne LiDAR imagery has previously been employed to study gullies under forest canopy (James et al., 2007). Automatic classification of gully erosion (Evans & Lindsay, 2010; Castillo et al., 2011) was not undertaken due to the morphology of constructed drains on valley fills being like that of gullies. The heads of gullies were counted for each dataset while observing whether the gullies were associated with retention cells, the valley fill faces or backfill, enlarged drains, roads, or the periphery of MTR/VF landscapes but not associated with retention cells (Supp. Fig 1). Enlarged constructed drains were considered gullies if an asymmetry between groin drains or dramatic enlargement was readily visible in the LiDAR slopeshade (Supp. Fig. 1D). The number of gullies per unit area was calculated by dividing the number of gullies by the total area of mined landscape. Gullies formed in landslide deposits associated with MTR/VF were not counted.

The areal extent of MTR/VF-associated landslides occurring along the perimeter of the mined landscape was mapped for two datasets, Amherstdale (WV) and Floyd-Pike (KY), by manually delineating landslide scarps and deposits from LiDAR-derived slopeshades. Landslides occurring within valley fills were quantified for all nine datasets. Landslide head scarps in valley fills were measured from the LiDAR data. Manual delineation of landslides from LiDAR imagery has been successfully utilized in forested environments where aerial imagery is not adequate (Eeckhaut et al., 2007; Konsoer & Kite, 2014). Areas of hillslopes with higher relative surface roughness (Glenn et al., 2006), head-scarps that abruptly exhibit high slope values, and deformation within valley fills that deviates from geometric design were used as visual indicators of landslide activity (Supp. Fig. 2). Landslides not occurring directly within valley fills were required to “scallop” the edges of the MTR/VF landscape to be considered associated with it. Deposits covering mining roads were used as another indicator. Care was taken to ignore landslides associated with legacy (pre-SMCRA) contour mining, which has caused many unstable slopes in these areas (Bell et al., 1989).

Results

Field Work Observations

Failure or overtopping of retention cells, small (~1 m deep, ~2 m wide, and variable length) constructed ponds which attenuate runoff, led to substantial erosion in two cases. Overtopping or breaching of a retention cell margin led to the erosion of a 3.2 m wide and 1.1 m deep gully on a colluvial sideslope within the Copperas 5 catchment (Fig. 5a). Copperas 5 is a center-drain style fill, which allowed the gully to erode into the unprotected interface of the valley fill face and the colluvial sideslope for 35 m (Fig. 5b). The gully channel could be seen in the October 2010 LiDAR data, and live vegetation and leaf litter were present within the gully during field work, indicating inactivity. Another retention cell was observed to have failed along a haul road in upper reaches of the Whitman 9 catchment. The failure induced a debris flow that eroded a ~2 m wide track into colluvium and terminated as a poorly sorted, lobate deposit on a topographic bench (Supp. Fig. 3). This feature was not observed in the LiDAR data.

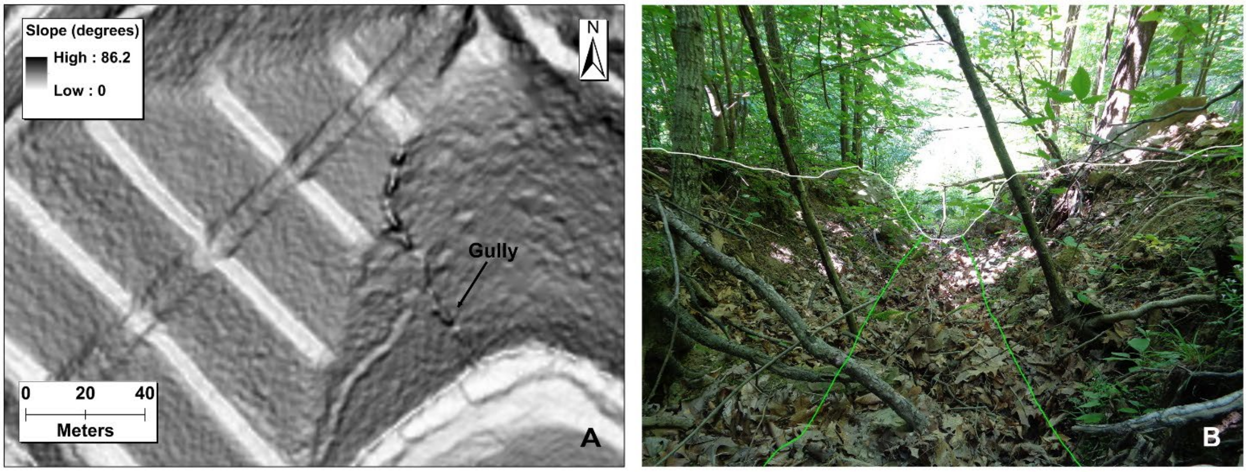

Figure 5. Gully caused by overtopping of a retention cell within Copperas 5. (A) LiDAR slopeshade with gully location. The gully extends over 60 m with the lower section eroding into the valley fill face. The upper section is separated from the lower by a slope failure. (B) Field photo looking downslope from within the gully's upper section. The white line demarcates the top of the banks and end of the upper section while the green outlines the bottom of the banks. The max width is 3.2 m, and the max depth is 1.1 m.

The intentional routing of water from of a group of connected retention cells over a low-point brim caused a gully to form upon a colluvial sideslope within the Whitman 12 catchment (Fig. 6a and 6b). At the widest section, the gully was 5 m wide and 1.5 m deep. Measurement from LiDAR data showed that the gully extended 74 m down the sideslope from its head, which was 35 m below the retention cells. Within the Whitman 16 catchment, intentional discharge from an overflow pipe outlet on a large retention cell eroded into a slope. The gully extended 105 m downslope from the road to the edge of a valley fill; and from there extended a farther 115 m along the sideslope-valley fill interface. LiDAR data observations described later will show that erosion due to retention cell interactions are widespread upon the MTR/VF landscape.

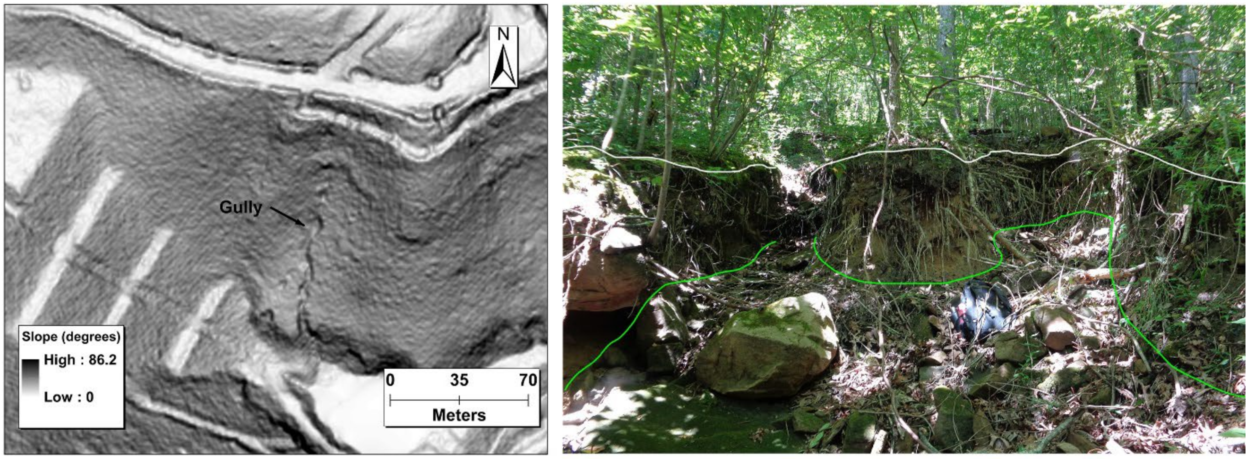

Figure 6. Gully initiated by intentional discharge from a set of retention cells within Whitman 12. (A) LiDAR slopeshade of the gully which extends ~74 m. (B) Upslope view from gully. The maximum width here is 5 m, and the depth is 1.5 m.

Several gullies were inferred to be caused by water flowing over the edges of a valley-fill terraces. Within Whitman 8, a 1.1 m deep by 2.6 m wide (at the largest cross section) gully occurred for 27 m between two terraces with a small wetland on the upper terrace providing the runoff. Living, pronated grass above the gully head indicated that a flowpath to the gully was still active. This gully was present in the LiDAR data, but a post-processed GPS point taken above the present-day gully head showed that it extended 8 m farther by 2017. This wetland-overflow mechanism initiated two smaller gullies elsewhere within Whitman 8. A 4.5 m long gully with a maximum cross-sectional area of 0.4 m^2 occurred within Whitman 18 at edge of the terrace where water is routed into the constructed groin drain.

Erosion induced by seepage occurred in several catchments. The largest example was an arcuate feature in the Whitman 8 catchment with a 2.6 m wide by 1.1 m deep scarp, but no visible upslope flowpath (Supp. Fig 4). Although this feature was seen in the LiDAR data, there was little vegetation present in 2017, indicating active erosion or adverse hydrological conditions for revegetation (Dunne, 1990). This was located above a non-designed spring-fed step-pool channel running down the center of the toe of valley fill (an erosional feature). A circular depression with a diameter of 1 m and a depth of 0.5 m was directly in front of the large seepage feature and above the stream. Whitman 15 also showed some signs of subsurface-induced erosion with a small gully, measuring 0.5 m deep and 0.5 m wide at the head scarp, with no observed flowpath above the gully head. Fluvial erosion within constructed drains was evidenced by finer sediments that appeared to be preferentially eroded from toe sediments along the edge of the constructed drains of Copperas 1 and Whitman 11. The fluvial channels eroded into colluvial slopes that intersect the toes of valley fills within Whitman 14, 17, and 19. The abundance or severity of erosional landforms observed in the field study areas did not appear to be associated with the age of the valley fills or catchment drainage area.

LiDAR Data Observations of Erosional Landforms

Gullies

Gullies were observed in all LiDAR datasets. Across the nine datasets, 991 manually classified gullies occurred across 375 km^2 of MTR/VF affected land. Gullies were associated predominantly with retention cells located on the periphery of the MTR/VF landscape, constituting 53.5 ± 10.9 percent of total gullies. Gullies associated with roads and peripheral gullies not associated with retention cells had means of 15.2 ± 6.4 and 14.6 ± 6.2 percent, respectively. Steep, colluvial slopes below the mined landscape incur the bulk of the erosion in all three cases. Valley fill face and backfill associated gullies were the least abundant. Table II shows the percentage for each class for all datasets.

The Perry-Knott-Breathitt dataset (Fig. 7) contained the greatest number of gullies (349) and most gullies km^{-2} (5.0). An increase in gullies km^{-2} moving southwest from West Virginia towards east-central Kentucky was observed in the data (Table II). The Cannelton (WV) dataset did not follow this trend. This may be due to Cannelton containing the greatest proportion of “old” valley fills in all the West Virginia datasets with 50% of valley fills constructed in the 1980s-early 1990s. As valley fill construction methods have changed through time (OSM, 2002), the age can determine not only the amount of exposure to erosion-inducing storm events, but the construction methods employed. Cannelton showed an elevated percentage of gullies occurring as enlarged constructed drains and peripheral gullies not associated with retention cells. The two Kentucky datasets, Perry-Knott-Breathitt and Floyd-Pike, both showed higher percentages of gullies occurring within valley fill faces or backfill material with 24.9 percent and 12.3 percent, respectively.

Table II. Gully observations for the nine LiDAR datasets with the number of observed gullies, gullies per unit area, and percentage of each type. Gullies km^{-2} shows an increasing trend going from east to west save Cannelton, which contains the greatest proportion of older valley fills.

Dataset	# of Gullies	Gullies (km^{-2})	Retention (%)	Roads (%)	Valley fill (%)	Peripheral (%)	Enlarged Drain (%)
Birch River, WV	25	1.1	44.0	24.0	4.0	20.0	8.0
Clay-Nicholas, WV	82	1.3	57.3	25.6	6.1	4.9	2.4
Boone-Kanawha-Raleigh, WV	84	1.8	57.1	21.4	2.4	14.3	4.8
Wharton, WV	59	1.8	66.1	11.9	5.1	11.9	5.1
Amherstdale, WV	121	2.3	63.6	13.2	5.8	16.5	0.8
Holden, WV	82	2.5	62.2	12.2	8.5	4.9	12.2
Floyd-Pike, KY	106	3.3	39.6	12.3	12.3	23.6	12.3
Cannelton, WV	83	3.7	57.8	7.3	2.4	20.4	12.0
Perry-Knott-Breathitt, KY	349	5.0	33.5	9.5	24.9	15.2	16.9

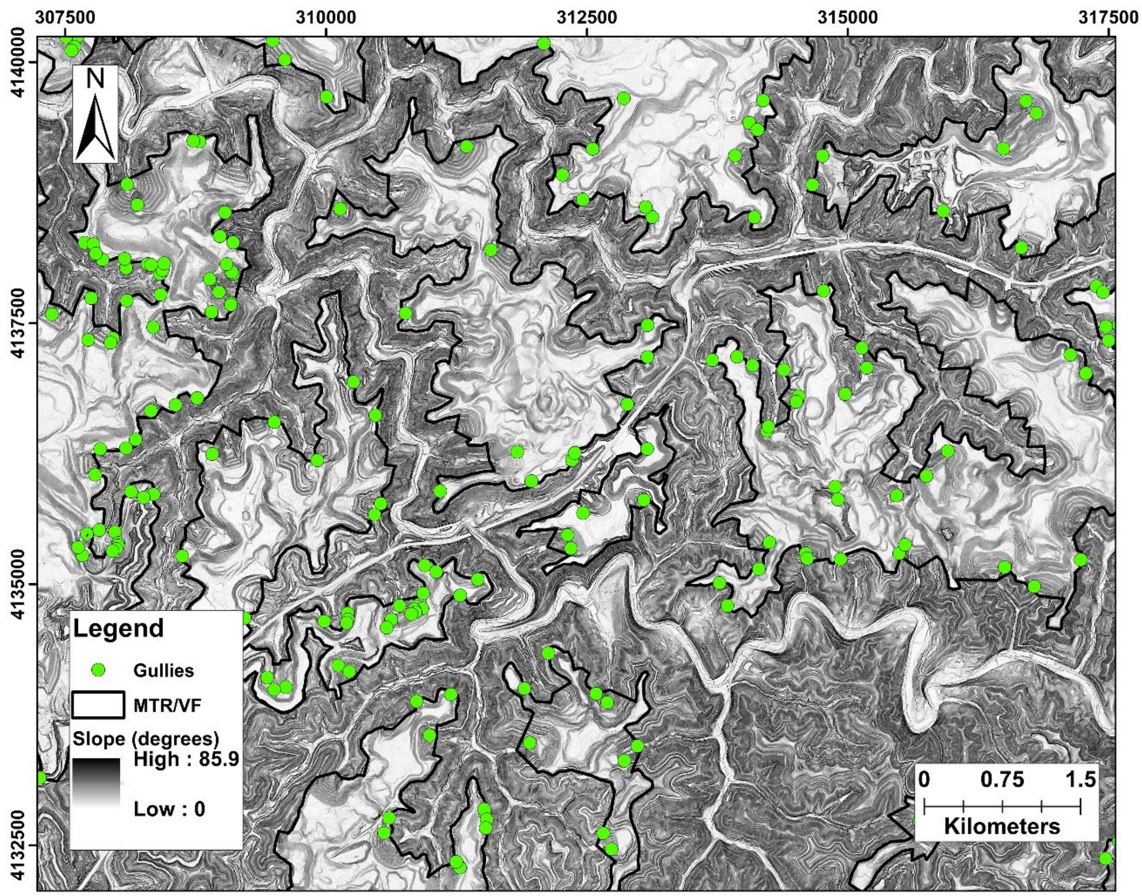

Figure 7. LiDAR-derived slopeshade of Perry-Knott-Breathitt (KY) dataset with most of the observed gully head locations shown in green. Gullies were primarily associated with retention cells in all nine datasets. The periphery of the MTR/VF landscape was observed to be more prone to gully erosion in all datasets.

Landslides

The Floyd-Pike (KY) dataset exhibited many more and somewhat larger landslides than the Amherstdale (WV) dataset (Fig. 8). Floyd-Pike contained 125 landslides within 32.06 km^2 of MTR/VF land (3.9 slides km^{-2}) while Amherstdale contained 15 landslides within 51.63 km^2 (0.3 slides km^{-2}). The median area disturbed by an individual landslide (scar and deposit) in the Floyd-Pike dataset was 8956 m^2 while the Amherstdale median was 4179 m^2. There were many gullies within landslide deposits that were not included in the quantification of gully erosion. Floyd-Pike also had 13 landslides on valley fill faces, while Amherstdale had only two, despite its larger area. The arcuate head scarps and downslope convexities exhibited by five of the landslides in the Floyd-Pike dataset suggests rotational movement, which is characteristic of slumps (Hungr et al., 2014). The largest slump main scarp was 13 m in height and 126 m from flank to flank. The Perry-Knott-Breathitt (KY) dataset contained three small landslides and one large landslide located within valley fill faces. The large landslide involves a near complete disorganization of the constructed topography of the valley fill face (Fig. 9). All KY landslides occurred in valley fills that have been fully released from reclamation bonds and will not be provided maintenance in perpetuity (confirmed via the Kentucky Surface Mining Information System, https://eppcgis.ky.gov/smis; Accessed May 2018). The other six West Virginia datasets contained only one landslide on the face of a valley fill, which was in the Boone-Kanawha-Raleigh dataset.

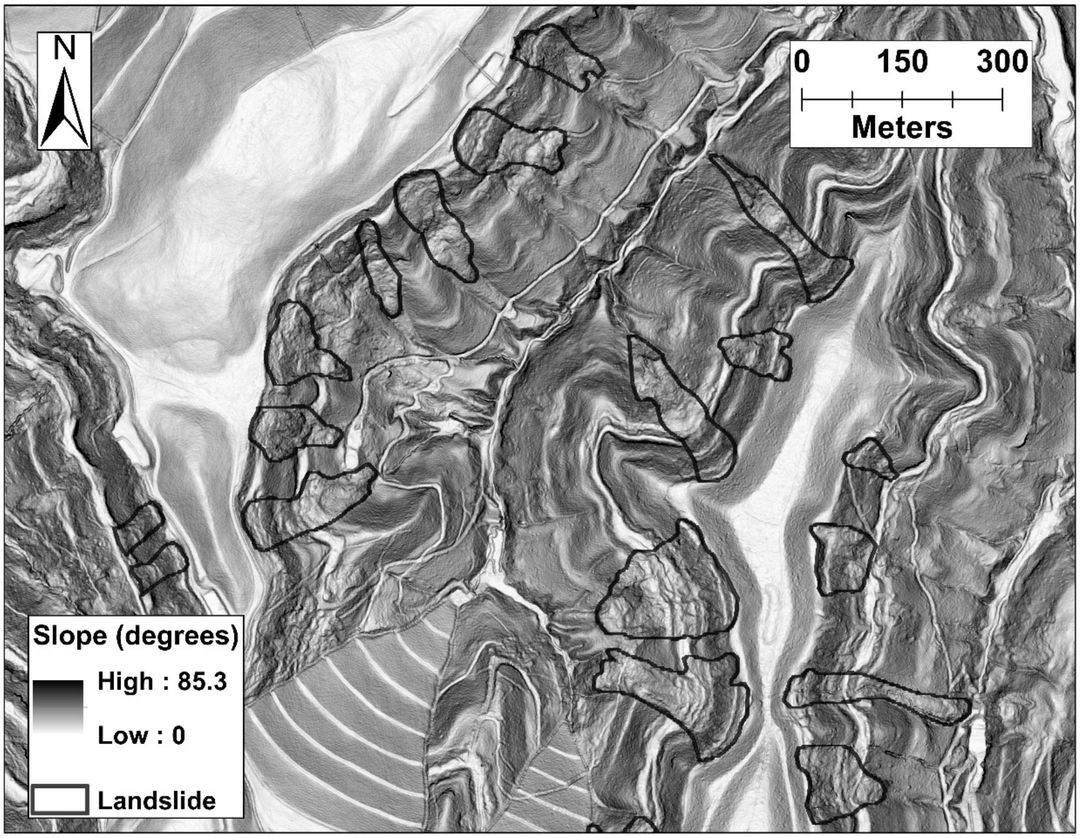

Figure 8. LiDAR-derived slopeshade of extensive landsliding on MTR/VF affected land in the Floyd-Pike (KY) dataset. Both median landslide area and density were greater in the Floyd-Pike dataset relative to the Amherstdale (WV) dataset. Landslides had to "scallop” the edge of the MTR/VF landscape to be considered associated with it.

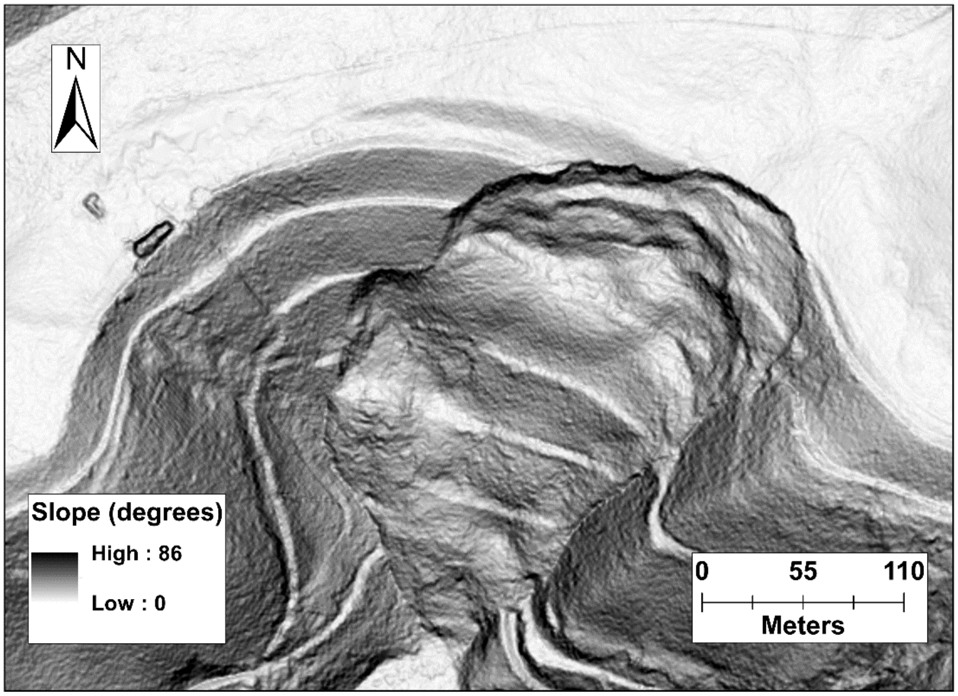

Figure 9. LiDAR-derived slopeshade of a large landslide disrupting the constructed topography of a valley in the Perry-Knot-Breathitt (KY) dataset. The valley is fully reclaimed and requires no maintenance.

Discussion

Gullies

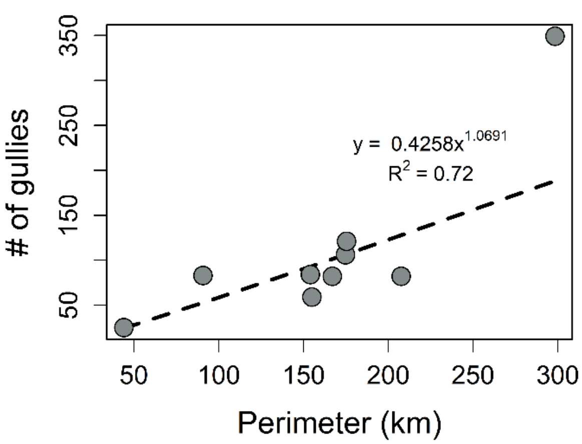

Figure 10. Relationship between perimeter of MTR/VF landscape in LiDAR datasets and number of gullies. The outlier (Perry-Knott-Breathitt) had the highest proportion of gullies occurring upon valley fills.

The LiDAR data observations showed that the retention cells ringing the periphery of the MTR/VF landscape are more prone to cause gully erosion on adjacent colluvial slopes rather than valley fills, an unexpected result. The perimeter of mined landscape explained much of the variance within the total amount of observed gullies ($R^2 = 0.72$, $p < 0.01$) when fit with a power law equation (Fig. 10). The lone outlier is the Perry-Knott-Breathitt (KY), which had the greatest proportion of gullies occurring on valley fills (~25%). Retention cells are analogous to drainage ditches along the edges of roads occurring in steep topography. Previous research has shown that the unnatural concentration of flow from artificially enhanced drainage area in ditches associated with roads can induce gully erosion (Montgomery, 1994; Wemple et al., 2001). Whether gully erosion associated with retention cells observed in the LiDAR datasets was predominantly induced by overtopping or intentional discharge is unknown. As retention cells are designed to attenuate runoff, cumulative failures may counteract the diminished stormflow response associated with the MTR/VF landscape (Zégre et al., 2014; Nippgen et al., 2017)**.** The overtopping of saturated terraces on valley fill faces leading to gully erosion may be analogous to a process observed in areas with abandoned agricultural terraces (Llorens et al., 1992). MTR/VF terraces are designed to slope away from the next outslope and towards the constructed drain. Local disturbances such as bioturbation or freeze-thaw of soil can disrupt the designed drainage pathways, enhancing saturation. The widespread gullying of colluvial slopes below the MTR/VF periphery warrants a new interpretation of the main findings of Fox (2009), which concluded that accelerated biogenic carbon export in MTR/VF affected streams was associated with bank erosion. According to the field and LiDAR data observations, gully erosion of colluvial slopes adjacent to MTR/VF may be the source of the extra carbon.

The trend of increasing gully occurrence per unit area from NE to SW along the extent of MTR/VF region could be explained two ways: finer grain sediments or construction practices. The OSM (2002) study on valley fills reported that the majority of friction angle values of mine spoils taken from Kentucky permit data were between 21-25◦. The same study listed the West Virginia values between 31-40◦. These data suggest that the materials composing the valley fills of Kentucky may have a finer grain size distribution (Bareither et al., 2008). Finer-grained, non-cohesive soils are more prone to erosion by concentrated water flow (Knapen et al., 2006), which is a primary gully formation processes (Bull & Kirkby, 1997). Petrological comparison of the rocks that compose valley fills across this proposed gradient has never been undertaken. An alternative explanation of disparate reclamation practices (e.g., more heavily compacted valley fill surfaces) should also be explored as surface mining is regulated by each state individually (EPA, 2011) and construction practices have varied through time (OSM, 2002). Ground truth data for a rigorous accuracy assessment (Congalton & Green, 2008) of features classified as gullies could be difficult to acquire as most of the MTR/VF land exists as inaccessible private property (Jaeger, 2015). As gully erosion was widespread on MTR/VF land, multi-temporal airborne LiDAR data may be the only way to track geomorphic change at a regional scale (Tarolli, 2014). As gully erosion has been observed on post-mining landscapes throughout the world (Haigh, 1980; Sawatsky & Tuttle, 1996; Sanz et. al, 2008), confirmation of the working hypothesis that gully erosion is an active process on the MTR/VF landscape is not surprising. The inevitable degradation of unmaintained, geometrically designed, synthetic landscapes such as MTR/VF seems to be generally accomplished via gully erosion (Schor & Gray, 2007).

Landslides

The abundant landslides in MTR/VF land of the Floyd-Pike LiDAR dataset reinforce the hypothesis that the sediments composing these reclaimed mining landforms may be finer grained relative to those in West Virginia, lacking the necessary shear strength to maintain stability. The landslides on the valley fills of the Floyd-Pike and Perry-Knott-Breathitt datasets were all on mine sites considered fully reclaimed and requiring no maintenance in perpetuity. This is the first reported evidence of landslides within fully reclaimed valley fills; valley-fill landslides reported in the OSM (2002) study were on sites in the process of construction or reclamation. Onsite investigation of the landslides would be needed for a better understanding of the processes and materials involved (Crawford et al., 2015). Historical DEMs could be used to provide data on the steepness of the slopes upon which the failed valley fills were built, as the OSM (2002) study linked steep foundation slope (i.e., the natural slope onto which the mining waste was dumped) to increased failure occurrence. As stability analysis methods used in construction of valley fills neglect the shear-strength-reducing effects of chemical and physical weathering over time (DePriest et al., 2015), more landslides should occur as recorded chemical erosion rates (solute flux) in valley-filled catchments are some of the highest on Earth (Ross et al., 2018). Multi-temporal LiDAR of the region affected by MTR/VF will be vital in the future to ascertain the risks associated with this newly discovered geohazard and to quantify geomorphic change due to mass wasting (Jaboyedoff et al., 2012).

Conclusions

Both field work and remote sensing observations show that gully erosion is an active, widespread process on the MTR/VF. Three gully initiation mechanisms acting upon MTR/VF landscapes are present in the field: overtopping/failure of retention cells, intentional discharge from retention cells, and flow over the edge of terraces on valley fill faces. The periphery of MTR/VF is most vulnerable to gully erosion due to the juxtaposition of steep, colluvial slopes and retention cells that artificially enhance drainage area. A trend of increasing gully erosion occurrence exists along a NE-SW transect across West Virginia and Kentucky that spans the region most affected by MTR/VF. Landslides are present along the MTR/VF perimeter above natural slopes in West Virginia land but appear to be more widespread in eastern Kentucky. Landslides are occurring within the fully reclaimed valley fills.

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Field and LiDAR data observations of erosion on anthropogenic valley fills and associated landscape produced by mountaintop removal/valley fill coal mining in Central Appalachia

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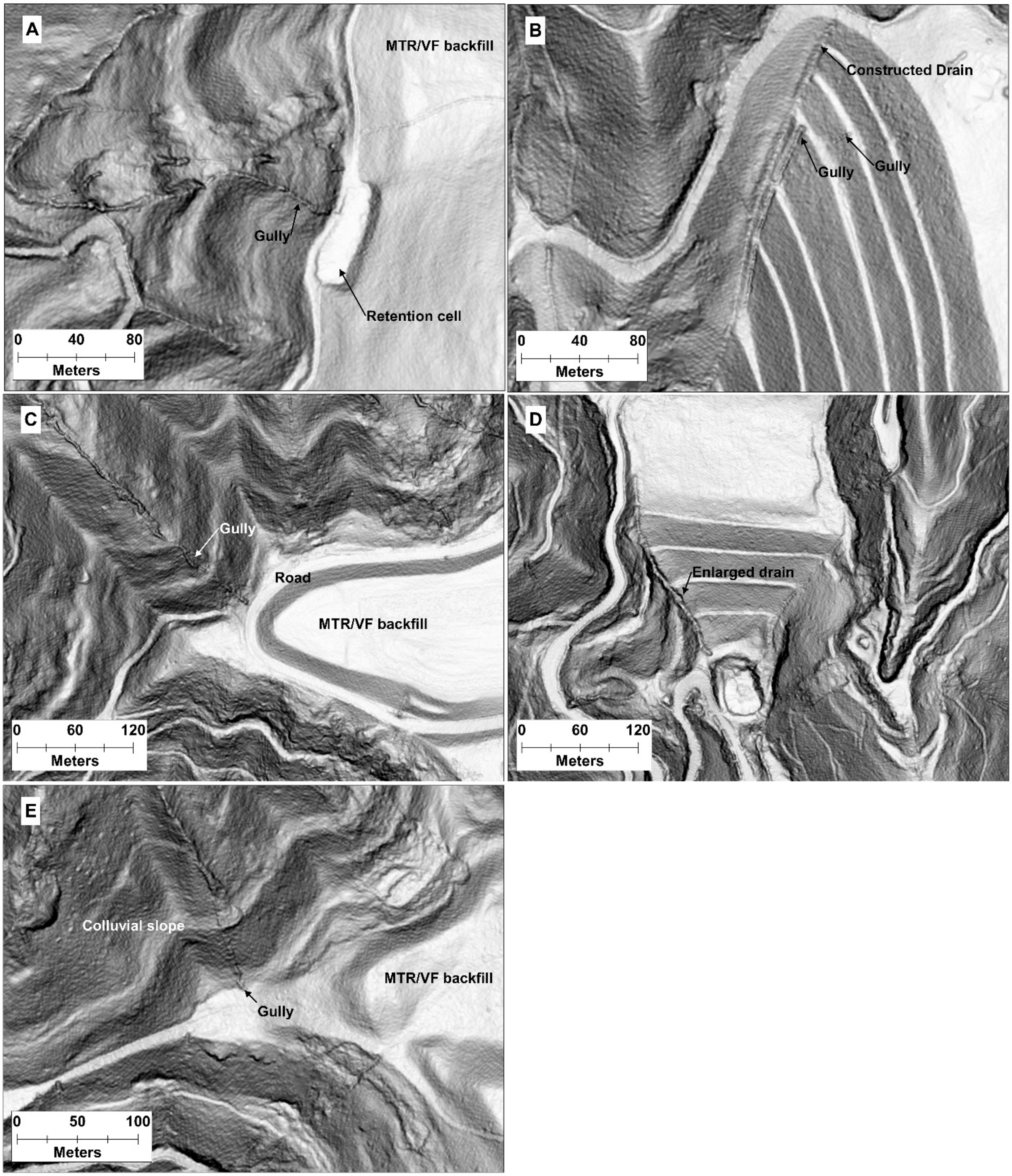
Supplementary Materials

Supp. Table I. Valley filled catchments assessed for erosional features. Age is derived from a West Virginia Department of Environmental Protection GIS shapefile of all known valley fills in the state, which shows the first year the valley fill could be detected via remote sensing methods.

Catchment	Study area	Drainage area (ha)	Drainage style	Age
1	Copperas	22.0	Center	2009
2	Copperas	15.9	Center	2009
3	Copperas	48.9	Center	2009
4	Copperas	52.1	Groin	2003
5	Copperas	14.9	Center	2003
6	Copperas	41.2	Center	2003
7	Whitman	20.2	Groin	1996
8	Whitman	18.6	Groin	1990
9	Whitman	35.0	Center	1990
10	Whitman	26.1	Center	2003
11	Whitman	11.6	Center	2003
12	Whitman	30.1	Center	2003
13	Whitman	23.4	Center	2003
14	Whitman	28.7	Center	1984
15	Whitman	16.8	Center	1990
16	Whitman	46.6	Center	Unknown
17	Whitman	35.7	Center	2003
18	Whitman	38.3	Groin	1996
19	Whitman	30.4	Center	2003

20	Whitman	20.1	Center	2003
21	Whitman	46.1	Center	2003



Supp. Figure 11. LIDAR-derived slopeshades of the five different types of gullies used in manual classification of gullies on the MTR/VF affected areas. (A) Gully associated with retention cell. (B) Multiple gullies occurring on the face of a valley fill. (C) Gully associated with a road. (D) Gullied constructed drain. (E) Gully associated with the periphery of the MTR/VF landscape but not associated with a retention cell.

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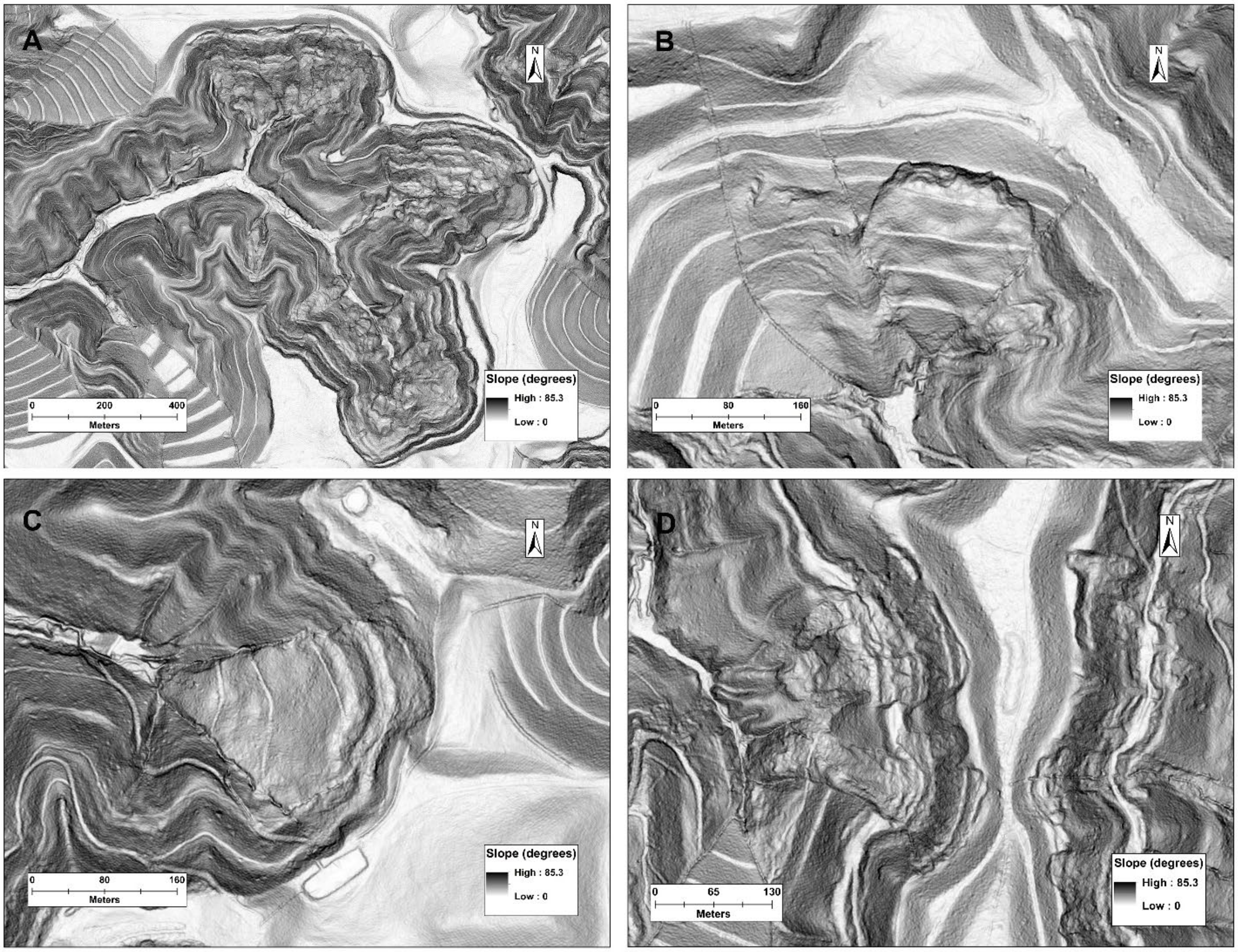

Supp. Figure 12. LiDAR-derived slopeshades of scenes that typify landslide indicators on the MTR/VF landscape. (A) Rough hillslope surface below MTR/VF (central axis of image) (B) Sharp break in slope associated with a landslide scarp in a valley fill. (C) Disruption of constructed topography by mass movement. (D) Landslides covering or destroying mine road below MTR/VF affected ridgetop.

Supp. Figure 13. ~2 m wide debris flow track within the Whitman 16 catchment. Complete failure of a retention cell along a disused haul road caused the debris flow. The valley fill is 100 m below the terminus of the debris flow deposit.

Supp. Figure 14. Upslope view of arcuate landform within the valley fill face of Whitman 8 inferred to be caused by seepage. The max width is 2.6 m, and max depth is 1.1 m. The landform is visible in the 2010 LiDAR data, yet remains partially unvegetated, indicating ongoing erosion or adverse hydrological conditions. The landform is located above a non-designed spring in the center of the valley fill. The measuring tape in the center is extended to 1 m.