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How Many Mountains Can We Mine? Assessing the Regional Degradation of Central Appalachian Rivers by Surface Coal Mining

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Supporting Information

ABSTRACT: Surface coal mining is the dominant form of land cover change in Central Appalachia, yet the extent to which surface coal mine runoff is polluting regional rivers is currently unknown. We mapped surface mining from 1976 to 2005 for a 19,581 km^2 area of southern West Virginia and linked these maps with water quality and biological data for 223 streams. The extent of surface mining within catchments is highly correlated with the ionic strength and sulfate concentrations of receiving streams. Generalized additive models were used to estimate the amount of watershed mining, stream ionic strength, or sulfate concentrations beyond which biological impairment (based on state biocriteria) is likely. We find this threshold is reached once surface coal mines occupy >5.4% of their contributing watershed area, ionic strength exceeds 308 μS cm^{-1}, or sulfate concentrations exceed 50 mg L^{-1}. Significant losses of many intolerant macroinvertebrate taxa occur when as little as 2.2% of contributing catchments are mined. As of 2005, 5% of the land area of southern WV was converted to surface mines, 6% of regional streams were buried in valley fills, and 22% of the regional stream network length drained watersheds with >5.4% of their surface area converted to mines.

INTRODUCTION

The rivers of Central Appalachia (southern West Virginia (WV), eastern Kentucky and Tennessee, and southwestern Virginia) support among the highest levels of biodiversity and endemism in the temperate zone [1] and drain watersheds that contain among the richest coal reserves in North America.[2] Prior to 1970, nearly all coal mining in this region was underground, but since 1975 coal production in Central Appalachia has been increasingly derived from surface coal mining (SI Appendix Figure 1).[3,4] Surface mining allows companies to mine seams of coal that are too shallow and too thin to mine profitably or safely with traditional underground mining approaches. These shallow coal seams are accessed by first removing the overlying mountain ridges with explosives and then excavating the underlying coal.[5,6] Surface mining and mine reclamation activities are now the dominant drivers of land use change in this sparsely populated region.[7]

As a result of the expansion of surface coal mining, Central Appalachia has the highest rates of earth movement in the United States,[8] as each surface mine generates large quantities of waste rock that are typically disposed of in adjacent stream valleys. The resulting valley fills can bury headwater streams under 10s to 100s of meters of waste rock,[5,6] and both the mines and their associated valley fills release alkaline mine drainage (AlkMD) directly into regional headwaters. Pyrite minerals in coal residues release sulfuric acid,[9] and the production of this strong acid within a matrix of carbonate bedrock neutralizes the acidity generated by pyrite dissolution and releases high concentrations of coal-derived sulfate ions (SO_4^{2-}) accompanied by elevated concentrations of calcium, magnesium, and bicarbonate ions (Ca^{2+}, Mg^{2+}, HCO_3^-).[10,11] Alkaline mine drainage is thus characterized by an increase in pH, alkalinity, and ionic strength in receiving streams that is often accompanied by concentrations of manganese (Mn) and selenium (Se) that may exceed established toxicity standards.[5,12]

Much attention has been paid to the burial of streams and the losses or deformities of sensitive stream biota immediately below valley fills that can be attributed to AlkMD.[5,12−16] Yet there has been no effort to quantify the cumulative downstream impacts of surface mining that result from the addition of AlkMD from many individual mines into river networks.

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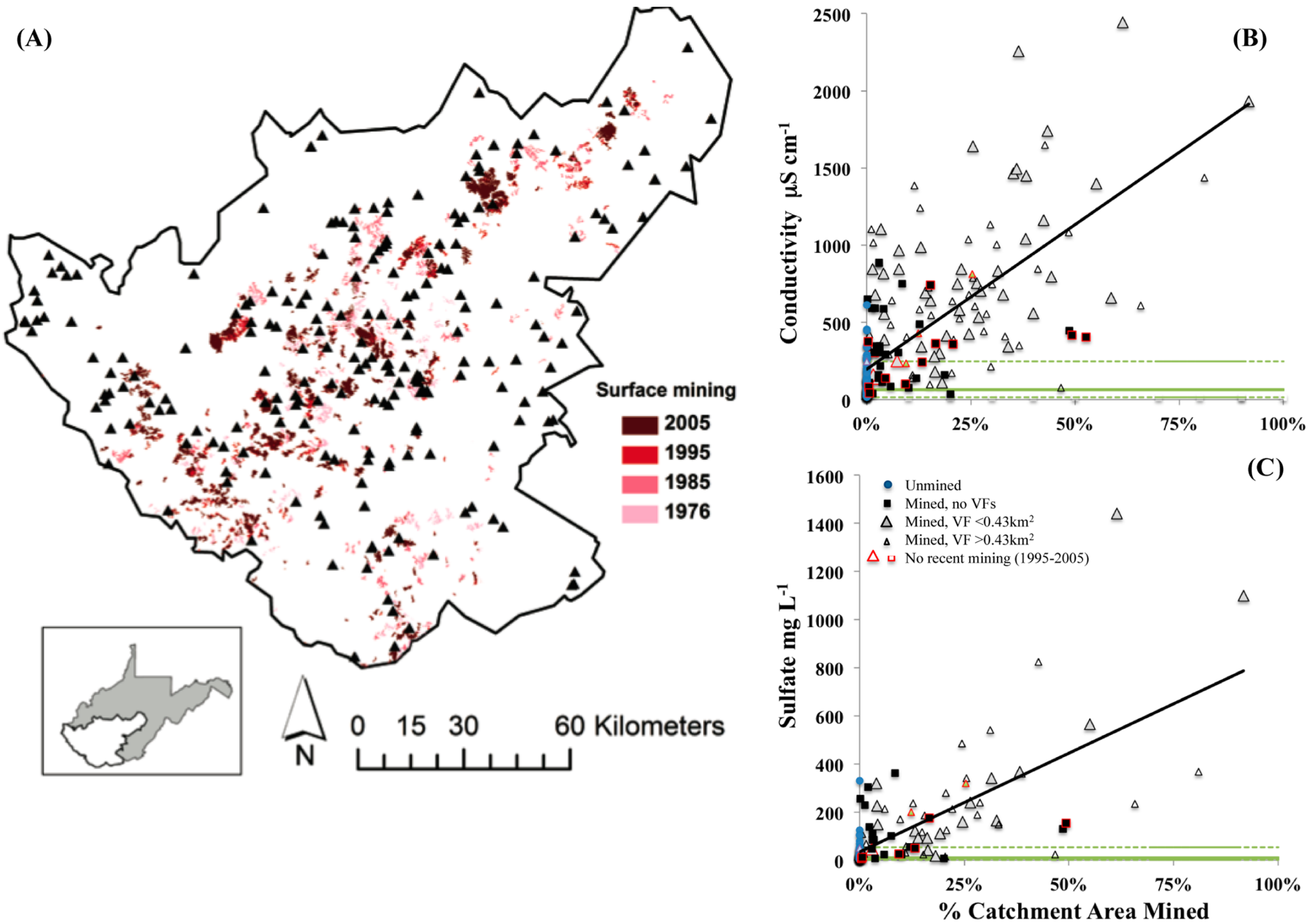

Figure 1. (A) The 19,581 km^2 study area in southern West Virginia (location in inset). Redscale shading shows the extent of surface mining in the region, with increasingly dark colors representing the estimates by successive decades. All 223 sampling points included in our statistical analyses are marked on the map as black triangles. (B) Streamwater conductivity is related to the areal extent of mining within the contributing catchment by Conductivity = 1873.7(%Mining) + 197.2 (R^2 = 0.48; p < 0.0001) [shown as solid black line, n = 223 sites]. (C) Streamwater sulfate is related to the areal extent of mining within the contributing catchment by Sulfate = 821.1 (% Mining) + 34.5 (R^2 = 0.50; p < 0.0001) [shown as solid black line, n = 144 sites]. In panels B and C dashed lines show the minimum and maximum values, and the solid green line shows the mean values reported for 241 WV Mountains ecoregion reference sites. Symbols outlined in red indicate catchments without any detectable surface mining in 1995 or 2005 (for these sites, surface mines were detected in 1976 or 1985 imagery).

In this paper our goals were to: (1) examine how the areal extent of catchment surface mining relates to water quality and the abundance of intolerant aquatic organisms in receiving streams; (2) identify critical levels of catchment mining and AlkMD pollution beyond which intolerant stream macroinvertebrate taxa are lost and at which streams are likely to be classified as biologically impaired based on regional bioindicator scores; and (3) to use this information to provide a first estimate of the cumulative, regional degradation of Central Appalachian stream ecosystems.

■ METHODS

Linking Mining Extent and Water Quality. We prepared comprehensive maps of surface coal mining activity for a 19,581 km^2 study area within southern West Virginia using digital analysis of Landsat images acquired from the National Land Cover Database (NLCD) in 1976, 1985, 1995, and 2005 [17] (Figure 1A, details provided in SI Appendix (Section 1)). This area represents 32% of the area of the entire Central Appalachians ecoregion 62,010 km^2. Using decadal imagery allowed us to measure the extent of both active and reclaimed mines and to calculate cumulative estimates of the extent of mining in the region over this four-decade time period. To better understand the variation in mining approaches, we also overlaid a spatial inventory of valley fills provided by the WV Department of Environmental Protection (WVDEP).[18]

We linked these spatial data sets to an extensive data set of stream chemistry and macroinvertebrate numerical abundance records for samples collected between 1997 and 2007 from the WVDEP (acquired July 2010). Each sample unit in the database was included in our initial analyses if it 1) could be conclusively mapped to a stream identified within the National Hydrography Database (NHD+);[19] 2) had aquatic macroinvertebrate samples collected during late Spring and Summer (April to August) that were identified to the lowest practical level of taxonomy, usually genus; and 3) included stream electrical conductivity measurements (hereafter conductivity) as a measure of ionic strength made at the time of macroinvertebrate sampling. If a candidate site was sampled more than once, we used only the most recent sampling date. For sites meeting these preliminary screening criteria, we delineated their contributing catchment areas and determined their land cover. We excluded from the data set any catchments that were not fully contained within our mapped study area and those for which active mining permits were reported but for which we detected no surface mining activity from our image analysis (further details in SI Appendix (Section 2)). The resulting data set included 459 unique sample locations.

We used NLCD land cover data[17] to remove watersheds that were heavily influenced by development. In the initial data set of 459 sites, we found that development was negatively correlated with both mining and conductivity because surface mines are rarely developed in heavily populated areas. Based on a threshold analysis of macroinvertebrate responses to % catchment development for all watersheds without mapped surface mining or mining permits (further details in SI Appendix (Section 3)) we eliminated all sites draining catchments with development impacts greater than 4.3% development. The final data set contained 223 unique field samples from streams draining catchments with low levels of development and a wide range of surface mining activity (0–92% of catchment area).

In our data set "unmined streams" (0% mining) do not represent pristine or reference conditions, they simply do not contain surface mines (as of 2005), have active mining or coal processing permits, or have >4.3% of their land area in development. Roads, forestry, low-density development, or low intensity agriculture occur in many of these unmined catchments. On average these unmined sites tended to have higher conductivity and ion concentrations than reference sites and had macroinvertebrate assemblages that were degraded relative to state reference sites (SI Appendix, Table 1). Unmined streams therefore provide a realistic representative sample of land use in the region for areas where future mining may occur. We also compare water quality and macroinvertebrate taxonomic composition for our data set to data from 241 sites in the same ecoregion that the state of WV recognizes as high quality reference sites ("reference" as defined in [20]). Twenty-three of these reference sites occurred within our study area. Since this regional subsample was not statistically different from the larger statewide data set for any water quality or biological metric we examined (SI Appendix, Table 1), we draw comparisons with the larger regional reference data set.

Statistical Comparisons. We compared the average values for water quality parameters (conductivity, pH, and concentrations of SO_4^{2-}, Ca^{2+}, and Mg^{2+}), habitat quality, the number of intolerant macroinvertebrate genera and two state biological critieria between reference, unmined and mined streams using an ANOVA followed by Tukey's HSD. We examined the relationships between % mining and stream conductivity and sulfate concentrations using linear regressions. We found that our cumulative estimate of surface mining (based on 1976, 1985, 1995, and 2005 imagery) was more highly correlated with all water quality and biological parameters than the most recent estimate of surface mining activity (based on 2005 imagery alone) (SI Appendix, Table 2). Therefore we used the cumulative mining impact estimate (hereafter % mining) in all subsequent analyses.

Examining Macroinvertebrate Responses to Mining and AlkMD Gradient. To describe the relationship between stream macroinvertebrates and the three covarying stressor gradients (% catchment mined, stream conductivity, and stream sulfate concentrations) we used two complementary statistical approaches in tandem. First, we used generalized additive regression models (GAM) to fit continuous response relationships of macroinvertebrate community metrics to each gradient. We selected three regionally important community metrics as response variables for GAM regression: 1) the number of intolerant genera, a single variable index used in biocriteria scores that is a direct measure of the number of taxa from a sample possessing tolerance scores ≤3;[21] 2) West Virginia Stream Condition Index (WVSCI), a family level multimetric index used by West Virginia as a narrative biocriteria;[20] and 3) Genus-Level Index of Most Probable Stream Status (GLIMPSS), an enhanced multimetric index that utilizes genus-level taxonomic determinations.[22] Second, we used Threshold Indicator Taxa Analysis (TITAN)[23,24] to examine individual and cumulative macroinvertebrate taxa responses to each stressor gradient and validated our TITAN results using a series of sensitivity analyses (further details in SI Appendix (Section 4)).

Use of GAM. We used GAM regression because graphical evaluation of scatterplots and of residuals from linear regression revealed a nonlinear pattern between macroinvertebrate response variables and each stressor gradient. GAMs are well suited for fitting response relationships that are nonlinear and where the precise functional form between the independent and dependent variable is not known *a priori*.[25,26] We also used GAMs because their efficacy has been demonstrated in modeling macroinvertebrate community metric responses to multiple stressors in this same region.[27−29] Finally, GAMs allowed us to model the stressor-response relationship after controlling the effect of instream habitat quality, a variable that influences community metrics independently of catchment mining and stream chemistry. We used the rapid bioassessment protocol (RBP)[21] habitat scores recorded by the WVDEP as our estimate of habitat quality. This assumption is supported by the low correlation coefficients for RBP vs mining, conductivity, and sulfate of (correlation coefficients of −0.09, −0.17, and −0.13, respectively) (SI Appendix, Table 3).

We used the resulting GAM models to estimate the point along each of the three covarying stressor gradients where, *on average,* the biological community will fall below the impairment thresholds attributed to WVSCI and GLIMPSS (details of GAM models in SI Appendix Section 5). We used the index scores as reported for each stream by the WVDEP. The impairment thresholds are set at 68 (WVSCI) and 52 (GLIMPSS) by the developers of each index.[20,22] Currently, the state of WV uses the WVSCI score as the metric for interpreting the narrative criteria for biological impairment.

Use of TITAN. We contrasted results from GAMs with those derived using TITAN, a different method characterizing the magnitude, direction, and uncertainty of responses of individual taxa to gradients in mining, conductivity and sulfate.[23,24] TITAN seeks the value of a predictor variable that maximizes association of individual taxa with one side of the partition. Association is measured by IndVal, computed as the product of the percentage of sample units in which a taxon occurred and the percentage of the total number of individuals captured by each partition.[23] Bootstrapping is used to identify significant indicator taxa.[30] A taxa is determined to respond positively (positive responders) or negatively (negative responders) to the gradient of interest if 1) the frequency and abundance of the taxa always responds in the same direction to changes in the stressor (the direction of the change is significant (p < 0.05) and in the same direction for at least 95% of the 500 bootstrapped runs =*"high purity"*) and 2) resampling of the data

Table 1. Results for Biological Responses to Increases in (A) Catchment Mining; (B) Stream Conductivity; or (C) Stream Sulfate Concentrations[a]

Response Variable	Analysis Type	R^2	Threshold estimate mean	95% CI of estimate	Affected River Length (km)	% River Network affected
A. Mining Thresholds or Change Points in Units of % Catchment in Surface Mines (See Figure 2)						
cumulative individual responses	TITAN	n/a	0.64%	0.02−2.2	4308	32.8%
WVSCI score <68	GAM	0.25***	4.50%	4.1−5.4	2834	21.6%
GLIMPSS score <52	GAM	0.34***	3.20%	2.0−6.3	3390	25.8%
B. Conductivity Thresholds of Change Points in Units of $\mu S\ cm^{-1}$ (See Figure 3)						
cumulative individual responses	TITAN	n/a	283	178−289	-	-
WVSCI score <68	GAM	0.34***	308	245−385	-	-
GLIMPSS score <52	GAM	0.47***	308	240−390	-	-
C. Sulfate Thresholds or Change Points in Units of mg SO_4^{2-} L^{-1} (n = 144 and n = 88 Sites) ***Data Shown in* SI Figure 6						
cumulative individual responses	TITAN	n/a	50	27−57	-	-
WVSCI score <68	GAM	0.23***	50	48−58	-	-
GLIMPSS score <52	GAM	0.35***	52	48−76	-	-

[a]The table provides the R^2 for each GAM (***indicates a p value <0.001) as well as the impairment threshold or change point estimate and its 95% confidence interval derived from both GAM and TITAN analyses. For each mining threshold estimate, we determined the amount of the regional river network (13,128 km) that drains catchments with a higher proportion of their area in surface mines than the upper bound of the 95%CI.

set is consistently different from randomly distributed data (at least 95% of 500 bootstrapped runs are significantly different from a random distribution (at $p < 0.05$) ="*high reliability*"). The sum of IndVal z-scores is then used to identify the predictor value and confidence limits along the gradient associated with the maximum decline in negative responders, (z-) or increase in abundance of all positive responders (z+) (see SI Section 4B for more detailed description and sensitivity analyses).

Estimating Regional Impacts. For every point along each stream reach comprising the regional river network we estimated the percentage of the contributing catchment that had been surface mined. This was done using the ArcGIS *weighted flow accumulation* tool with binary pixel classification (e.g., area of surface mining = 1; other areas = 0), where each pixel was assigned to the mining category if it was identified as a mined area in any of the Landsat images. By combining these analyses with the NHD+ flow direction data set we were able to determine the area of historical surface mining within the contributing watershed of any stream location. We then calculated the total river network extent draining catchments having a greater percentage of their areas mined than the percent surface mining values we estimate would lead to biological impairment or the loss of sensitive stream taxa as determined in our GAM models (Table 1). We restricted this scaling exercise to catchments less than 5000 ha in area since this was the maximum catchment size found within our stream sample data set.

RESULTS AND DISCUSSION

Water Quality Patterns Associated with Surface Mining. We estimate that 5% of the land surface within our study area was converted to surface mines between 1976 and 2005 (Figure 1A). Within our data set 126 of 223 locations drained catchments with surface mining that ranged from 0.03 to 92% of the contributing catchment area. Conductivity within our data set ranged from 18 to 2553 $\mu S\ cm^{-1}$, streams draining catchments with any amount of mining (hereafter mined streams) had significantly higher conductivity (626 ± 34 $\mu S\ cm^{-1}$, mean ± SE) than unmined streams (118 ± 39 $\mu S\ cm^{-1}$) (Figure 1B). For comparison, the average conductivity of state reference streams throughout WV was 64 ± 3 $\mu S\ cm^{-1}$, and no samples from these locations had conductivity values exceeding 247 $\mu S\ cm^{-1}$ (Figure 1B, SI Appendix Table 1). Similarly, stream sulfate concentrations were significantly higher for streams draining catchments with mining (197 ± 21 mg SO_4^{2-} L^{-1}) than for streams without surface mining in their catchments (28 ± 20 mg SO_4^{2-} L^{-1}; $p < 0.0001$) (Figure 1C). Sulfate concentrations in state reference streams averaged 9 ± 0.5 mg SO_4^{2-} L^{-1} (SI Appendix Table 1). The amount of each catchment's surface area that had been mined (hereafter % mined) explained ∼50% of the variation in conductivity and stream SO_4^{2-} concentrations (Figure 1B,C). In our data set conductivity was strongly positively correlated with SO_4^{2-}, Mg^{2+}, and Ca^{2+} concentrations (correlation coefficients of 0.93, 0.90, and 0.90, respectively), three of the most common constituents of AlkMD[12,31](SI Appendix Table 3).

While the increase in conductivity and AlkMD constituents with increasing watershed % mining is highly significant, ∼50% of the variation in conductivity remains unexplained. Temporal variation in streamflow likely drives much of this residual variation, with discrete storm events and seasonal changes in flow affecting the concentrations of mine-derived solutes in stream runoff. Field measures of conductivity at a single site in the Mud River, a stream draining a large surface coal mining complex within our study area, varied from 1082 to 1864 mS cm^{-1} over the course of one summer due to variation in flow.[12] Variation in the age or type of surface mining may also explain some of this variation. Although at present our land cover data are too limited to make effective statistical comparisons, incorporating information on valley fill size suggests that catchments containing mines with large valley fills are more likely to have high concentrations of AlkMD constituents (Figure 1 B,C).

Stream Macroinvertebrate Responses to Mining and AlkMD Stressor Gradients. Stream macroinvertebrates responded similarly to each of the correlated gradients of increasing % mining, stream conductivity, and sulfate concentrations (Figures 2 and 3 Supplemental Appendix Figure 6). State reference streams support an average of 16 ± 0.2 (SE)

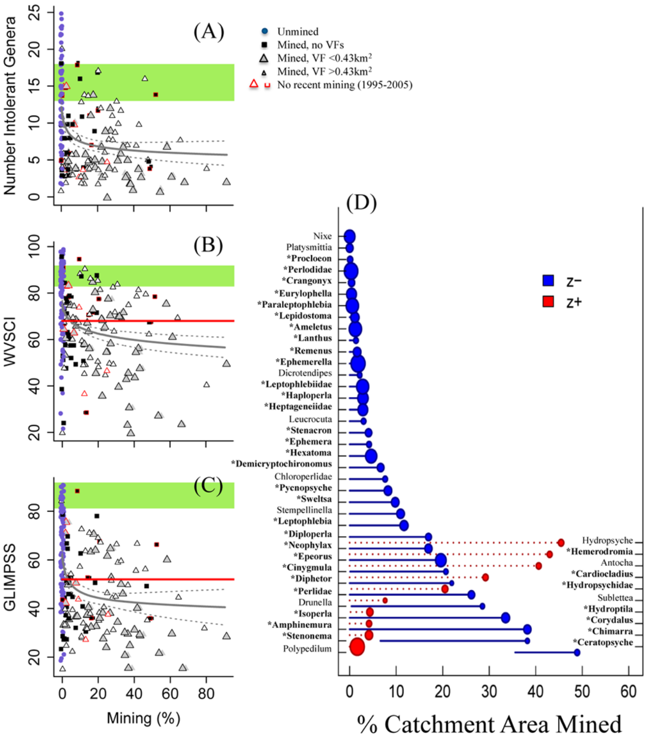

Figure 2. Changes in stream macroinvertebrate community composition metrics (the number of (A) intolerant taxa, and the biological index scores (B) WVSCI and (C) GLIMPSS) are graphed relative to the % of catchment area in surface mines. (D) Threshold Indicator Taxa Analysis (TITAN) results for taxa that respond strongly to the % mining gradient. In A–C generalized additive model (GAM) fits to the entire data set are shown as solid black lines; dashed black lines show the 5 and 95% confidence intervals of the parameter estimates. Each generalized additive model (GAM) accounts for variance in the number of intolerant taxa and the biological indices WVSCI and GLIMPSS after accounting for variance due to differences in habitat quality recorded by WVDEP. The green shaded area in each graph shows the 25th–75th quantile range for 241 reference sites in the mountains ecoregion of WV. Solid red lines in panels B and C are set at the WVSCI and GLIMPSS impairment thresholds of 68[20] and 52.[22] In (D) z scores indicate the point along the environmental gradient at which the maximum change in abundance or frequency of occurrence for taxa is detected. This change can be positive (+z, blue circles) for taxa that become more frequent or abundant along the gradient or negative (-z, red circles) for taxa that decline in frequency or abundance. The points are placed at the upper limit of the 95% CI based on 500 bootstrap change-point estimates for each taxon, horizontal lines indicate 95% CI, and point size is proportional to the indicator value (IndVal) z-score. In the WVDEP database some taxa are not identified to genus; these ambiguous taxa (as per ref 33) are identified only to family but remain in our analysis.

intolerant macroinvertebrate taxa, while the mined streams in our sample set typically contained less than half as many intolerant genera (7 ± 0.5 (SE)). Unmined streams in our data set (n = 97) supported an average of 13 ± 0.5 (SE) intolerant genera. The diversity of intolerant taxa is a critical component of biological indicator scores, and thus the WVSCI and GLIMPSS scores reported for unmined streams (77 ± 2 (SE) and 65 ± 2 (SE), respectively) were typically above the impairment thresholds for each index (68, 52) and were consistently higher than were reported for streams draining mined catchments (63 ± 2 and 45 ± 2, respectively). For comparison, the 241 state reference streams had WVSCI and GLIMPSS scores of 86 ± 0.4 (SE) and 75 ± 1 (SE), respectively.

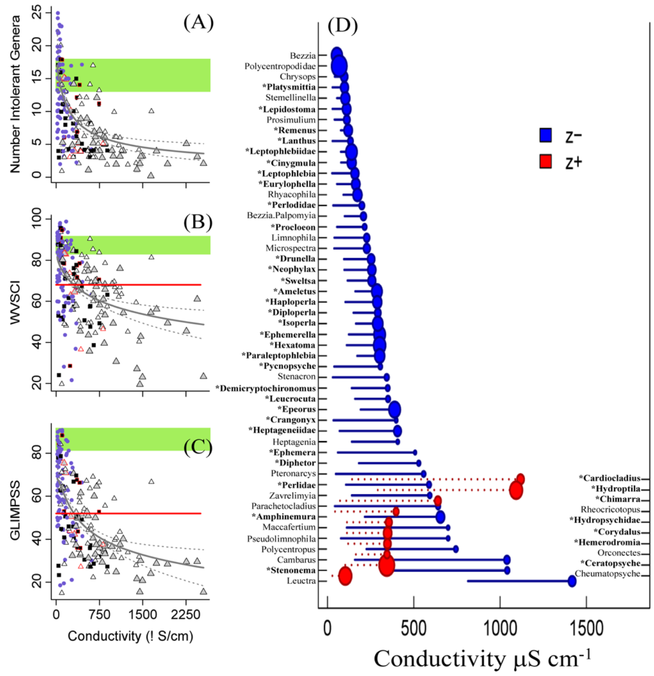

Figure 3. Changes in stream macroinvertebrate community composition metrics (the number of (A) intolerant taxa, and the biological index scores (B) WVSCI and (C) GLIMPSS) are graphed relative to stream conductivity. (D) Threshold Indicator Taxa Analysis (TITAN) results for taxa that respond strongly to the increasing conductivity gradient. Details of the graph are identical to those described for Figure 2.

Stressor Gradient 1, Mining. The diversity of intolerant stream macroinvertebrates declined steeply with increasing % mining, with GAM accounting for ~32% of the variance in the number of intolerant taxa across sites (Figure 2A). Biological indices rely heavily on the abundance and diversity of intolerant taxa, thus the WVSCI and GLIMPSS scores of receiving streams showed similar decreases with increasing % mining. For both WVSCI and GLIMPSS scores, the GAMs captured 25% and 34 of the variation in the index scores, respectively (Figure 2B,C, Table 1). A GLIMPSS index value below 52 is the threshold defining biological impairment, which the GAM model predicts for catchments having more than 3.2% of their contributing catchment in surface mines (Table 1). For the WVSCI index a score of 68 defines the threshold for impairment, which the GAM model predicts for catchments having more than 4.5% of their catchments in surface mines (Table 1).

Results from our TITAN analysis are consistent with the GAM results. TITAN analysis revealed that 37 of the 157 taxa showed significant declines with increasing % mining (Figure 2D, SI Appendix (Figure 2)). The nearly synchronous declines of the majority of sensitive taxa was consistent with a community-level threshold,[32] suggesting that surface mining of greater than 0.6% (95% CI of 0.02 to 2.2%) of the upstream catchment results in significant declines in the abundance of many taxa comprising downstream communities (SI Appendix (Figure 3A)). The taxa most sensitive to mining represent a variety of mayfly, stonefly, caddisfly, and beetle larvae characteristic of Central Appalachian streams that are known to be sensitive to water pollution.[13,22] Several taxa (n = 10) increased in relative abundance along the mining gradient, primarily genera of highly tolerant midges (Chironomidae) the tolerant caddisflies *Chimarra* and *Hydropsyche*, and the predatory dobsonfly *Corydalus* (Figure 2D, SI Appendix (Figure 3B)).

Stressor Gradient 2, Conductivity. As with the mining gradient, the diversity of intolerant macroinvertebrate taxa declined rapidly with increases in stream conductivity, with the conductivity model capturing more variation in the number of sensitive taxa than % mining (GAM, r^2=0.45; Figure 3A). Based on the GAM models once stream conductivity increases above 121 or 308 μS cm^{-1} GLIMPSS and WVSCI scores will typically fall below their respective impairment thresholds (Figure 3 B,C; Table 1). TITAN revealed significant declines in abundance for 50 of the 157-recorded taxa in response to rising conductivity (Figure 3D, SI Appendix (Figure 4)), with the greatest cumulative community diversity loss observed at 283 μS cm^{-1} (95% CI of 178−289 μS cm^{-1}) (Figure 3D, Table 1, SI Appendix (Figure 5A)). Ten species of tolerant caddisflies and fly larvae responded positively to increasing conductivity (SI Appendix (Figure 5B)). The estimates we derive from all three analyses are very close to the benchmark value of 300 μS cm^{-1} that was recently set by the U.S. EPA to be protective of Central Appalachian stream biota.[29] Identical analyses were conducted for the sulfate gradient, with results appearing in Table 1 and data and models presented in SI Appendix Figures 6−8).

All analyses consistently detected significant declines in the abundance of sensitive macroinvertebrates in mined streams, with those declines detectable at low levels of catchment mining and low concentrations of AlkMD. Several studies have previously documented effects of surface coal mines on receiving streams;[5,12−14] here we demonstrate that the spatial extent of mining within catchments determined via satellite imagery can be used to predict patterns in stream chemistry and macroinvertebrate community composition at much larger spatial scales. There are sites within our data set where higher than expected numbers of intolerant macroinvertebrates are recorded for streams draining heavily mined watersheds. We have insufficient information to determine whether these outliers provide useful counterexamples of the general tendency of surface coal mines to pollute downstream ecosystems with AlkMD, or if they are merely the result of the inevitable mismatches between the timing of stream sampling and our decadal estimates of mining activity for some sites. Incorporating estimates of valley fill area and volume into our estimates of mining intensity may further improve our understanding of these relationships.

Estimating the Impact of Surface Coal Mining on the Regional River Network. To estimate the cumulative potential impact of surface coal mining on the regional river network, we calculated the total length of streams in catchments having % mining that exceeds the value associated with the WVSCI and GLIMPSS impairment thresholds (Table 1). For this upscaling exercise we used the % mining values associated with the WVSCI and GLIMPSS thresholds (GAM models), or declines in sensitive genera (TITAN), that correspond to the upper 95% CI value for the model predictions. Thus, we are 95% confident that *the majority of* streams draining catchments with % mining exceeding these values will be biologically impaired. We estimate that the majority of catchments with >5.4% of their area in surface mines will have WVSCI scores below 68, indicating impairment. Approximately 2,834 km of the ∼13,128 river kilometers in the study area drain catchments with at least 5.4% of the catchment area occupied by surface coal mines (Table 1, Figure 4A). Using TITAN we found that significant reductions in the

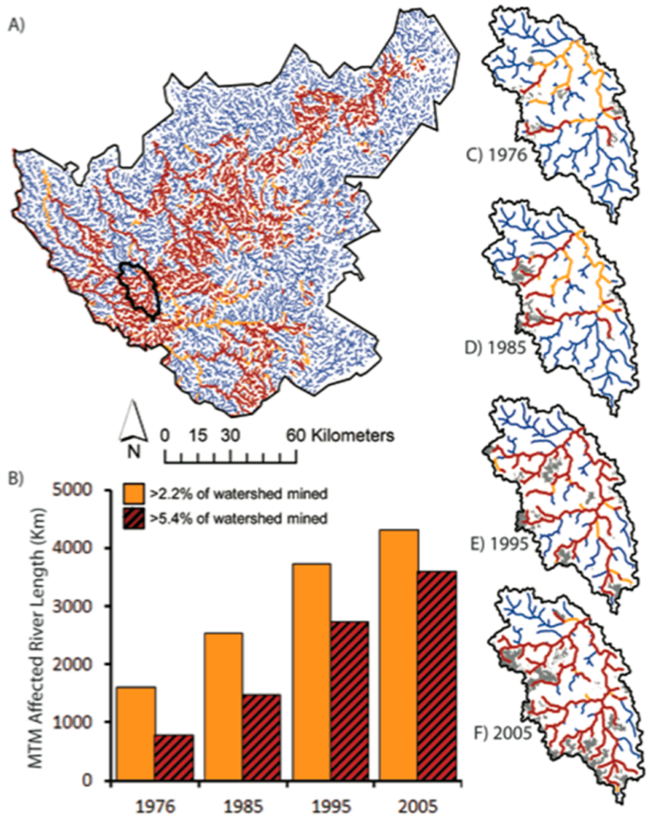

Figure 4. (A) A map of the river network of the study area shows our estimate of the extent of downstream biological impairment. Streams shaded blue have <2.2%, streams shaded orange have 2.2−5.4%, and streams shaded red have >5.4% of their catchments draining surface coal mines. (B) Decadal estimates of the cumulative number of river kilometers draining catchments with at least 2.2% (orange) or 5.4% (red) of their surface area in active or reclaimed surface mines. (C−F) Decadal estimates of the extent of surface mining (in gray) and downstream mining impacts (in orange and red as above) in the 270 km^2 Island Creek catchment, a tributary to the Guyandotte River.

diversity of intolerant macroinvertebrates likely result once 2.2% of a stream's catchment area is converted to surface mines (Table 1). Approximately 4,308 km of the regional river network drains catchments with ≥2.2% mining (Table 1, Figure 4A). These estimates are based on the cumulative extent of mining in the region between 1976 and 2005 and suggest that the rapid increase in the extent of surface mining in the region has been accompanied by a parallel rise in the extent of river network degradation (Figure 4 B−F).

Our analyses document that surface coal mines degrade water quality and substantially alter stream biota well downstream of their permit boundaries and that the extent and severity of these impacts within river systems are proportional to the areal extent of surface coal mining in the contributing catchment. We document strong correlations between % mining and AlkMD constituents at regional scales, consistent with a recent empirical study linking % mining and AlkMD constituents concentrations in one of the watersheds within this regional analysis, the Mud River, WV (USA).[12] We estimate that 22% of streams in the region drain catchments with mining extensive enough to be classified as biologically impaired based on state criteria, while an even greater extent of the river network (32% of stream length) drains catchments with enough mining influence to lead to the losses of many intolerant taxa.

Our findings suggest that the impacts of AlkMD pollution are extending well beyond the direct impacts of valley fills. Current WVDEP analyses estimate that 772 km of streams within our study area have been filled by surface coal mining overburden,[18] while our analyses suggest that significant biological impairment and biodiversity loss is occurring in 4–6X this stream length (2800–4300 km) as a result of the propagation of surface coal mining pollutants through the regional river network. Collectively, the weight of evidence among these methods demonstrates that dramatic losses of sensitive taxa occurs once streams exceed the range of conductivities (or sulfate concentrations) observed in reference streams or in situations where >2.2% of their catchment surface area has been mined. These analyses suggest that the many individual mines in the region are having additive effects and that more attention must be paid to the cumulative impacts of surface coal mining in this region.

■ ASSOCIATED CONTENT

Supporting Information

A supplemental appendix that includes 3 supplemental tables and 7 supplementary figures in support of statement in the text along with more detailed descriptions of our methods. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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