Do headwater streams recover from longwall mining impacts in northern West Virginia?

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West Virginia Water Research Institute

by:
Ben M. Stout III
Department of Biology
Wheeling Jesuit University
Wheeling, WV 26003
bens@wju.edu
(304) 243-2316

Abstract

The purpose of this study was to measure the extent of longwall mining impacts on headwater streams in northern West Virginia and address the question: do streams recover? This report encompasses two years of field research and compliments the report of June 30, 2003 entitled: Impact of longwall mining on headwater streams in northern West Virginia (Stout, 2003). During the first-year study it was found that approximately one-half of all headwater streams were impacted, resulting in dry stream segments, narrow stream widths, chemical imbalances, and depauperate biological communities compared to unmined or room-and-pillar mined reference streams. During the second year of field work two unmined and three room-and-pillar mined reference streams were re-sampled, and one unmined stream was added to the study design. Three streams that had been longwall mined five to six years ago were also re-sampled to assess repeatability of results and to look for signs of possible recovery. Three streams that had been longwall mined nine, ten, and twelve years prior to fieldwork were added to the study to look for evidence of temporal recovery.

Physical, chemical, and biological measurements were collected at six to eight sites along the gradient of each stream beginning at the source and working at measured downstream intervals. General Linear Models Analysis of Variance was used to compare average longwall mined versus reference streams in their physical, chemical, and biological dimensions. The interaction term in two-way analysis of variance was used to determine if spatial recovery occurred along the course of longwall mined headwater stream gradients, after testing for the two main effects: reference versus longwall mined, and distance from the source. Regression analysis was used to assess temporal recovery based on changes that may occur over the time elapsed since mining, and to see if physical, chemical, and biological conditions got better, stayed the same, or got significantly worse a decade after mining occurred.

Significant physical differences in average longwall mined versus reference streams included 31% less stream width and 0.8^{o}C lower temperature. Eighteen percent of sampling sites in longwall mined streams were dry. Stream width did not recover to reference conditions spatially along the headwater stream gradient. Stream width did not recover temporally when comparing recently mined streams to those that had been mind over one decade prior to sampling. Differences in stream temperature between longwall mined and reference streams did not change over the stream gradient, but did appear to recover somewhat over time.

Longwall mined streams averaged 100 *u*mhos higher conductivity, 11% lower dissolved oxygen, and 64 ppm greater alkalinity than reference streams. None of these conditions changed significantly over the course of the headwater stream gradient. Over time, conductivity and alkalinity in longwall mined streams remained elevated above reference conditions. Dissolved oxygen was lower in streams that had been longwall mined in the past compared to streams that had been longwall mined more recently. The chemistry of headwater streams did not recover to

reference conditions either spatially or temporally, and appeared to get worse over time in terms of dissolved oxygen concentrations.

Macroinvertebrate communities, the primary biological entities in headwater streams, were significantly degraded by longwall mining. For instance, macroinvertebrate abundance was 44% lower, diversity was 47% lower, and long-lived taxa were 51% fewer in longwall mined versus reference streams. No water was present at 18% of samples from longwall mined streams. An additional 17% of samples failed to support a minimum viable community of at least two individuals (minimum population) from each of two kinds of macroinvertebrates (minimum community) even though water was present at the time of sampling. Overall, our second year of field studies confirms the first year findings that longwall mined streams fail to support biological communities in approximately one-half of the headwater streams across the region.

Spatially, it was found that macroinvertebrate abundance was impacted more at the source than in the downstream reaches of longwall mined streams. On average most, but not all, longwall mined headwater streams had as many macroinvertebrates as reference streams once streams re-emerged in larger, 120 acre watersheds. No such recovery was evident temporally, and streams mined nearly a decade prior to sampling continued to exhibit the lower abundance characteristic of recently longwall mined streams. Diversity and longevity of the biological community failed to exhibit any evidence of recovery over space or time. Compared to reference streams, taxa richness remained consistently low along the longwall mined stream gradient and failed to recover in streams that had been mined over a decade prior to study. The EPT taxa, with life cycles requiring 9 to 22 months of residence as larvae in streams, failed to show signs of recovery over spatial or temporal gradients. The semivoltine taxa, which require 2 to 5 years of residence in atreams to complete the larval stage of their life cycles, also failed to recover spatially or temporally. Functionally, macroinvertebrate communities were similar regardless of longwall mining history. Leaf shredders and fine particle collectors dominated headwater stream communities, and algal grazers and predators were proportionally less abundant. The macroinvertebrate communities in longwall mined streams maintained their trophic balance even though they do not occur in one-half the headwater streams that they previously occupied across the longwall mining region of northern West Virginia.

Introduction

Longwall mining in the central Appalachian region fractures bedrock and results in loss of most springs and wells, and mining companies are generally required to replace household water supplies. Studies of wetlands (Schmid & Kunz, 2000) and large streams (Earth Science Consulants, 2001) in southwestern Pennsylvania, USA have addressed the impacts of full-extraction mining followed by subsidence on these respective landscape elements, but no studies have addressed impacts on spring-fed headwater streams in the region. These streams are often ignored or mistakenly referred to as "intermittent" or "ephemeral" due to their non-existence on widely-used 1:24,000 scale topographic maps (Meyer, et al, 2003). In fact, headwater streams can be expected to comprise greater than 80% of the total length of the stream network in a region draining a given watershed (Hynes, 1970).

Loss of headwater streams from the landscape could have significant ecosystem-level consequences for large rivers and for the surrounding forest. Headwater streams are regarded as exceptional in terms of performance in energy flow and nutrient retention within the complex network of forest and stream interrelations (Wallace *et al*, 1997). Forest litter sustains the energy and nutrient budgets of Appalachian headwater streams (Fisher & Likens, 1972; Likens, et al, 1970). Leaf shredding is the key industry in headwaters (Cummins, et al 1989), and the resulting downstream transport of energy and nutrients helps sustain larger river systems (Vannote, et al, 1980). The bulk of the energy assimilated by fine particle collectors in large rivers appears to originate in terrestrial ecosystems (Winterbourne, et al, 1984).

Stream-dwelling seal, spring, and northern two-lined salamanders are permanent residents and dominant vertebrate predators in West Virginia headwater streams, but many other amphibians also depend on headwater streams to provide suitable aquatic breeding sites in proximity to the forest (Green & Pauley, 1987). Other fauna, including birds, depend on the emergence of aquatic insects as a significant food source (Jackson & Fisher, 1986; Gray, 1993). Via their biological communities, headwater streams have the unique capacity to import low-quality, lignin and cellulose forest products (leaves and sticks) and convert that material into high-quality fats and proteins for export back to the forest in the form of insect emergence. Moreover, emerging insects are in a form readily consumed by a suite of forest species at a time coinciding with annual breeding and nesting cycles (Smith & Smith, 1996).

The purpose of this research was to measure impacts of longwall mining on headwater streams in northern West Virginia, and to determine if streams recover from longwall mining either spatially or temporally. Three hypotheses were tested. First, if longwall mining impacts on streams were benign, then the physical, chemical, and biological characteristics of longwall mined streams would not be significantly different than reference streams because streams were not completely dewatered. Second, if streams were dewatered near their sources then they would recover in their downstream reaches because subsided stream reaches eventually return to the surface. Finally, if streams are impacted by subsidence during longwall mining then they will return to reference conditions over time because continued subsidence over a period of years following longwall mining causes stream beds to heal themselves.

Methods

Field studies consisted of sampling streams at their source and at measured downstream intervals. Selection of suitable study streams was accomplished by determining the presence or absence of longwall undermining from mining maps available at West Virginia Geological Survey, permit records filed with State Department of Environmental Protection, and county tax maps. Within each mining region, longwall mined watersheds were compared with nearby reference watersheds that were geographically similar, but were either un-mined or room-and-pillar (bord and pillar) mined.

In the field, each stream was sampled by a four-person team on a single date. Each stream was sampled at the source (furthest upstream spring, or seep) and location recorded using Global Positioning Systems. The source was sampled for pH, conductivity, dissolved oxygen, and temperature using standardized field meters. Stream width was measured 10 times using a ruler or tape. Three investigators collected aquatic macroinvertebrates from a ten meter reach using any means practical (hand-picking, nets, pans, forceps) for a total of 10 minutes (timed). The resulting 30-minute composite sample was stored in a pre-labeled 250 ml plastic container, preserved in 80% ethanol, and returned to the laboratory. The team measured fifty meters downstream with a tape, recorded the GPS location, and repeated the sampling. Sampling was continued at 100 meter downstream intervals for a total of six to eight samples per stream.

In the laboratory, macroinvertebrates from stream samples were sorted and identified to the lowest practical taxonomic level, generally genus. Prominent taxa were reared to determine species. Chemical and biological data were compiled in spreadsheets and analyzed. Community-level metrics included taxa richness (number of kinds) as a measure of diversity, the number of EPT (mayfly, stonefly and caddisfly) taxa as an indication of the purely aquatic, relatively long-lived (generally >9 months aquatic) taxa, and the number of semivoltine taxa, those with aquatic larval life cycles that are greater than one-year in length as an additional biological measure of stream permanence. The percent abundance of each of four functional feeding groups (leaf shredders, fine particle collectors, algal grazers, predators) was calculated in order to compare the trophic status (energy balance) of communities at each site (Merritt & Cummins, 1996). Functional group composition was calculated only for samples containing communities as defined by a minimum of two individuals in each of two taxa. Basin geomorphology including watershed area (Allan, 1995), stream elevation, slope, and aspect were measured for each site using GPS coordinates and MapTech Software with US Geological Survey 1:24,000 scale data.

In analysis, 6-8 samples collected at regular intervals along the longitudinal stream gradient were representative of the entire headwater reach of each stream.

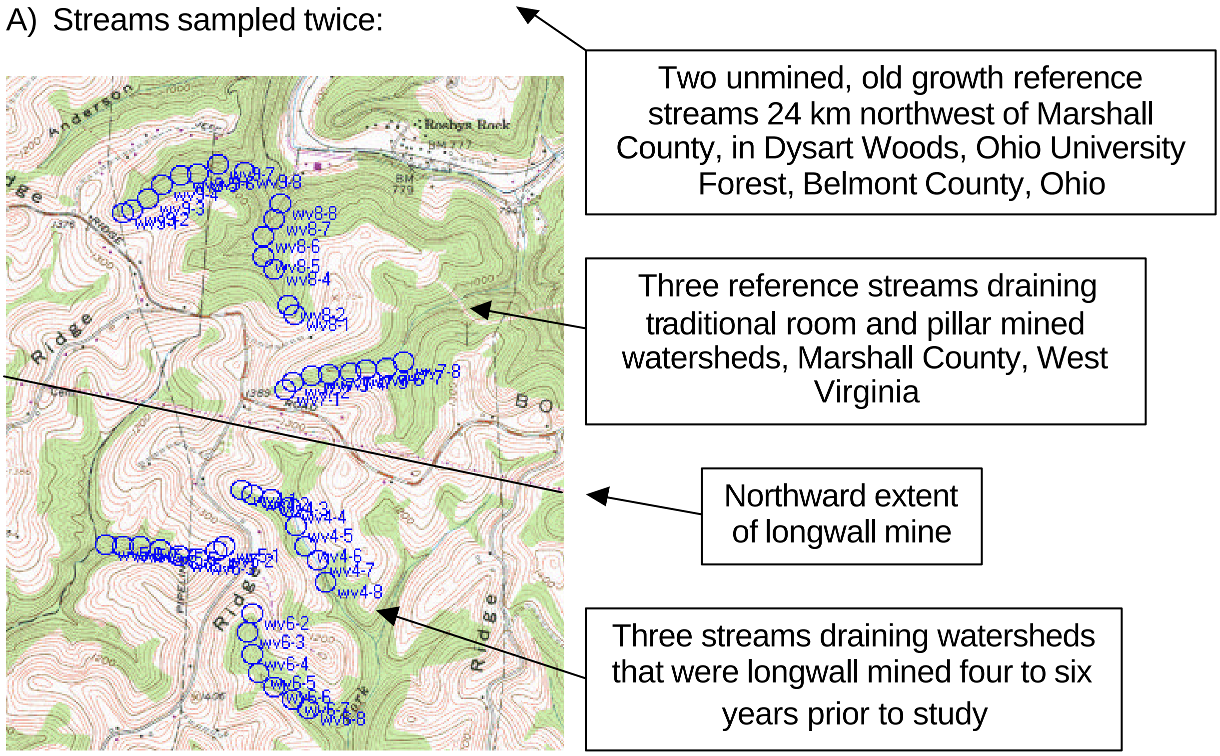
Samples site locations were randomly predetermined based on the source and prescribed downstream distance measurements. Average physical, chemical, and biological conditions of twelve longwall mined and eleven reference streams were compared using one-way General Linear Models Analysis of Variance followed by Dunnett's Test (NCSS, 2003). Two additional analyses were conducted to determine if streams recover from longwall mining either spatially or temporally. Spatially, the potential recovery of longwall mined versus reference streams along the downstream gradient was based on a significant interaction term ($p<0.05$) using two-way Analysis of Variance and testing for the main effects: distance from the source, and longwall mined versus reference stream. Temporally, regression analysis was performed to determine if significant changes occurred in longwall mined streams over time; an effect that would indicate whether streams recovered, stayed the same, or declined during the twelve-year period after mining.

Study sites

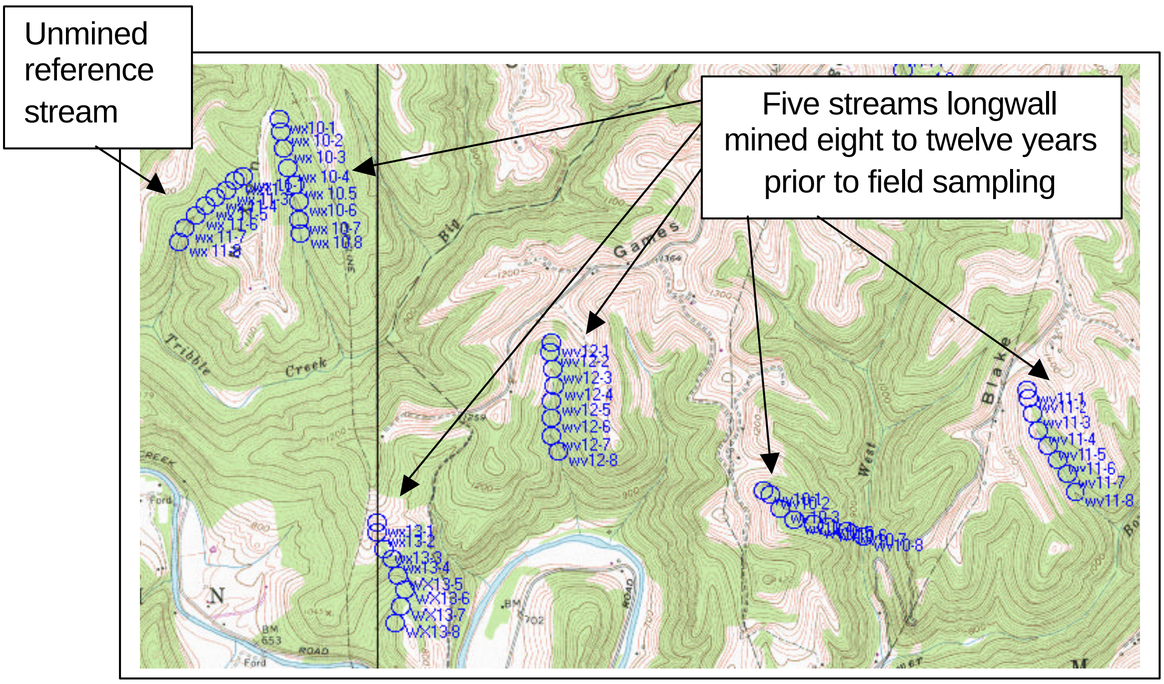
Fourteen different streams were sampled including 6 reference and 8 longwall mined streams (Map 1). Streams sampled once in June 2003 or June 2004 in Marshall County included 5 streams that had been longwall mined between eight and twelve years prior to study and one unmined reference stream.

Three longwall mined and five reference streams were sampled twice, once in June 2003 and again in June 2004. The three longwall mined streams sampled twice in Marshall County, West Virginia, had been longwall mined in 1997 and 1998. Three reference streams sampled twice in Marshall County were in a watershed adjacent to the longwall mined streams and had been room and pillar mined more than ten years prior to study. Two reference streams sampled twice in Dysart Woods, Belmont County, Ohio, drained an unmined, old-growth forest 26 km northwest of the Marshall County sites. Only six samples were collected from Dysart Woods streams.

A) Streams sampled twice:



B) Streams sampled once:



Powhatan Point Quad:Glen Easton Quadrangle

Map 1. Sampling locations in longwall mined and reference streams in Marshall County, West Virginia (1:24,000 United States Geological Survey data).

Results

Average physical characteristics of headwater streams

Reference and longwall mined watersheds had similar physical features with the exception of stream width and temperature (Table 1). Watershed drainage area above sampling points ranged from 1.1 to 137 acres and average watershed size was 43 acres. Streambed slope ranged from 30.5% near the top of basins to 3% in the downstream reaches. Average slope was 12 and 11% in reference and disturbed streams, respectively.

The width of streams draining longwall mined versus reference watersheds was significantly different. Longwall mined streams were on average 0.64 meters wide, whereas average reference streams were 0.93 meters wide. Water was present in all 79 samples from reference streams, whereas 16 of 88 samples (18%) from longwall mined streams were dry.

Instantaneous stream temperatures (at the time of sampling) were significantly different with averages of 16.1 and 16.9^{o}C in longwall mined and reference streams, respectively. Additionally, temperatures of 11.2 ^{o}C minimum to 21.4^{o}C maximum were more extreme in reference streams compared to a range of 13.7 to 20.8^{o}C in longwall mined streams.

Table 1. Mean (and 1 standard error) physical characteristics of streams and probability of no significant physical difference in samples from longwall mined (N=88) versus reference streams (N=79), and (ANOVA, Dunnett's Test ,*p<0.05).

	Reference streams		Longwall mined streams		
Physical measurement	Mean	(SE)	Mean	(SE)	Probability
Watershed area (acres)	41.5	(3.8)	43.8	(3.6)	0.646
Elevation (feet)	1091	(11)	1093	(10)	0.924
Stream slope (%)	12.1	(0.8)	10.9	(0.8)	0.277
Compass heading (degrees true N)	184	(9.3)	173	(8.8)	0.364
Median stream width (meters)	0.93	(0.06)	0.64	(0.05)	0.000*
Water temperature (^{o}C)	16.9	(0.2)	16.1	(0.3)	0.022*

Physical characteristics along headwater stream gradients

Streams originated as springs and seeps at elevations of 1140 to 1280 feet above mean sea level (Figure 1). Watershed drainage area ranged from 1.1 to 10.8 acres at the points where streams originated as springs or spring seeps. Average drainage area was 5.5 acres at the origin of reference streams and 6.0 acres at the origin of longwall mined streams.

Longwall mined streams were narrow compared to reference streams. On average, streams at their origin had median stream widths of 0.24 m in longwall mined streams and 0.47 m in reference streams. The width of average longwall mined streams did not achieve the width of average reference streams over the respective downstream gradients. Longwall mined streams were 1.1 m wide and reference streams 1.3 m wide in downstream reaches representing 100 acre watersheds. Lack of a significant interaction term (p=0.82) between the main effects indicated that longwall mined stream width did not recover to reference stream width over the course of the headwater stream gradients studied.

Instantaneous stream temperature was collected over the course of each day, starting at the top and working toward the bottom of watersheds. Temperature generally increased with increasing watershed size in reference streams due in part to increasing air temperature during the day, and in part to increasing distance of surface waters from their groundwater sources. In longwall mined watersheds, stream temperature remained relatively constant from the top to the bottom of the watersheds. As noted in the field and further indicated by stream width data, many of the longwall mined streams subsided in the upper reaches and resurfaced at some point downstream. Subsurface flow in subsided sections likely contributed to 1-2^{o}C lower summer daytime stream temperatures in areas where longwall mined streams resurfaced downstream. Instantaneous water temperature in 60 to 120 acre longwall mined streams was consistently lower than in analogous reference streams. Lack of interaction between main effects (p=0.26) indicated that instantaneous temperature of longwall mined streams did not achieve reference conditions.

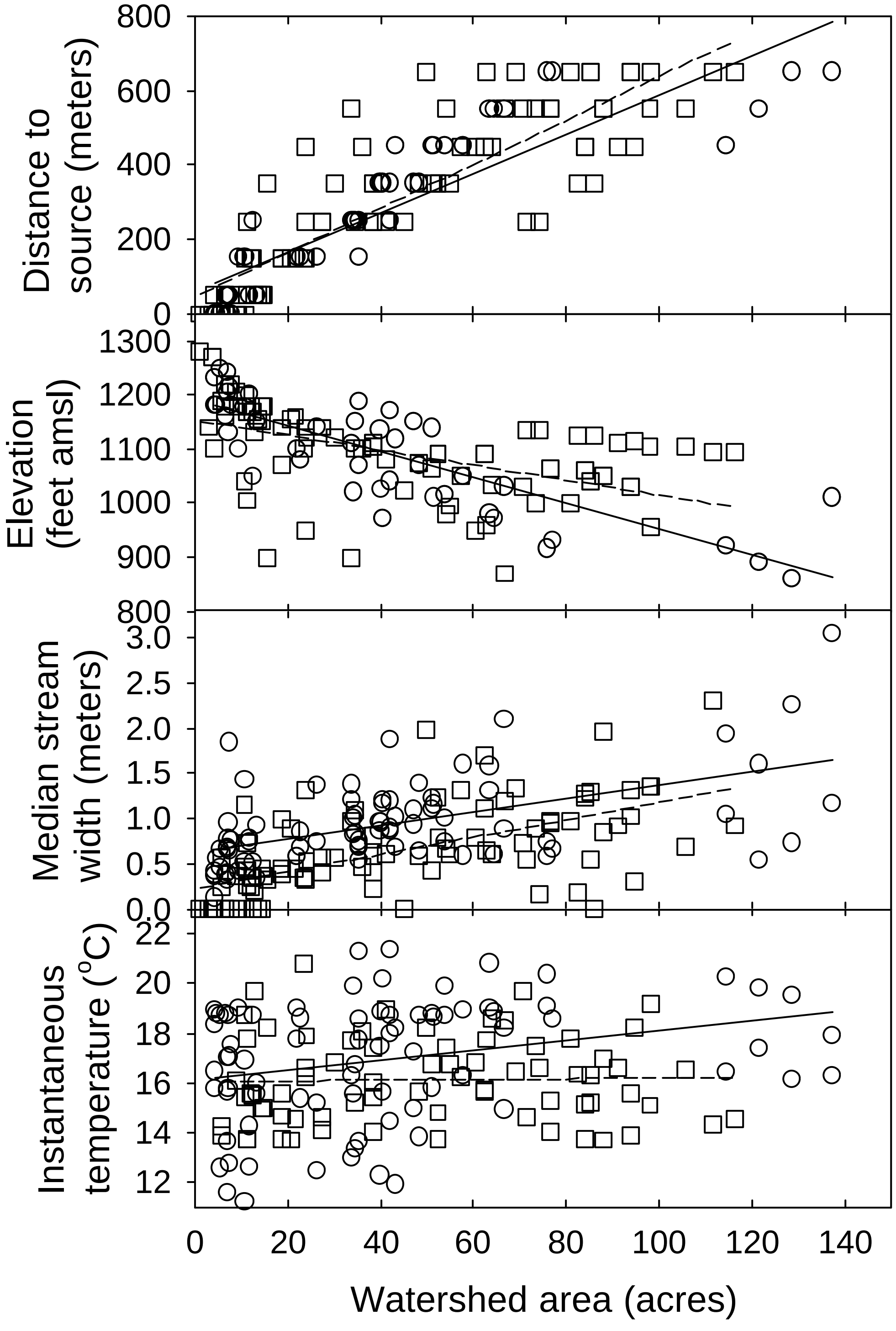


Figure 1. Scatterplot of physical attributes measured along headwater stream gradients comparing longwall mined (squares) and reference streams (circles). Least square means regression lines for samples from longwall mined (dashed, N=88) and reference (solid, N=79) streams (except temperature of longwall mined streams had only 72 samples due to dry stream beds at 16 of 88 sites).

Physical changes in longwall mined streams over time

The potential for temporal physical recovery of longwall mined streams was analyzed by comparing stream width and temperature because these attributes were significantly impacted by longwall mining. In this analysis, best fit regression lines were used to determine if time-induced trends existed among the longwall mined streams studied, and to determine if longwall mined streams had tendencies toward reference conditions over the decade after longwall mining occurred (Figure 2). Because average stream width was less in longwall mined versus reference streams, it was anticipated that if streams recover over time then stream width would be greater in streams that were mined nearly a decade prior to sampling than in streams that were longwall mined more recently.

A regression of stream width over the time elapsed since mining was not significantly different from zero ($p=0.48$), indicating no change in the width of longwall mined streams over time. Some longwall mined streams had widths similar to reference streams and others did not, but there was no trend in stream width with regard to elapsed time since mining. Regression analysis indicated that in longwall mined streams width does not change over time, and therefore physical recovery of longwall mined streams over time is not apparent. Some longwall mined steams are simply impacted more than others.

Stream temperature was lower when comparing average longwall mined versus reference streams (Table 1), and differences in stream temperature along the respective headwater stream gradients indicated that longwall mined streams did not achieve reference conditions (Figure 1). However, there did appear to be a trend to increasing temperature of longwall mined streams over time (Figure 2). Over 40% of the variation in summer daytime stream temperature could be explained by the time elapsed since mining occurred. Longwall mined streams appeared to achieve reference stream temperature approximately one decade after mining occurred. Although the width of longwall mined streams remains less than reference conditions, stream temperature patterns may reflect increased surface exposure following continued settling of the stream bed a decade post mining.

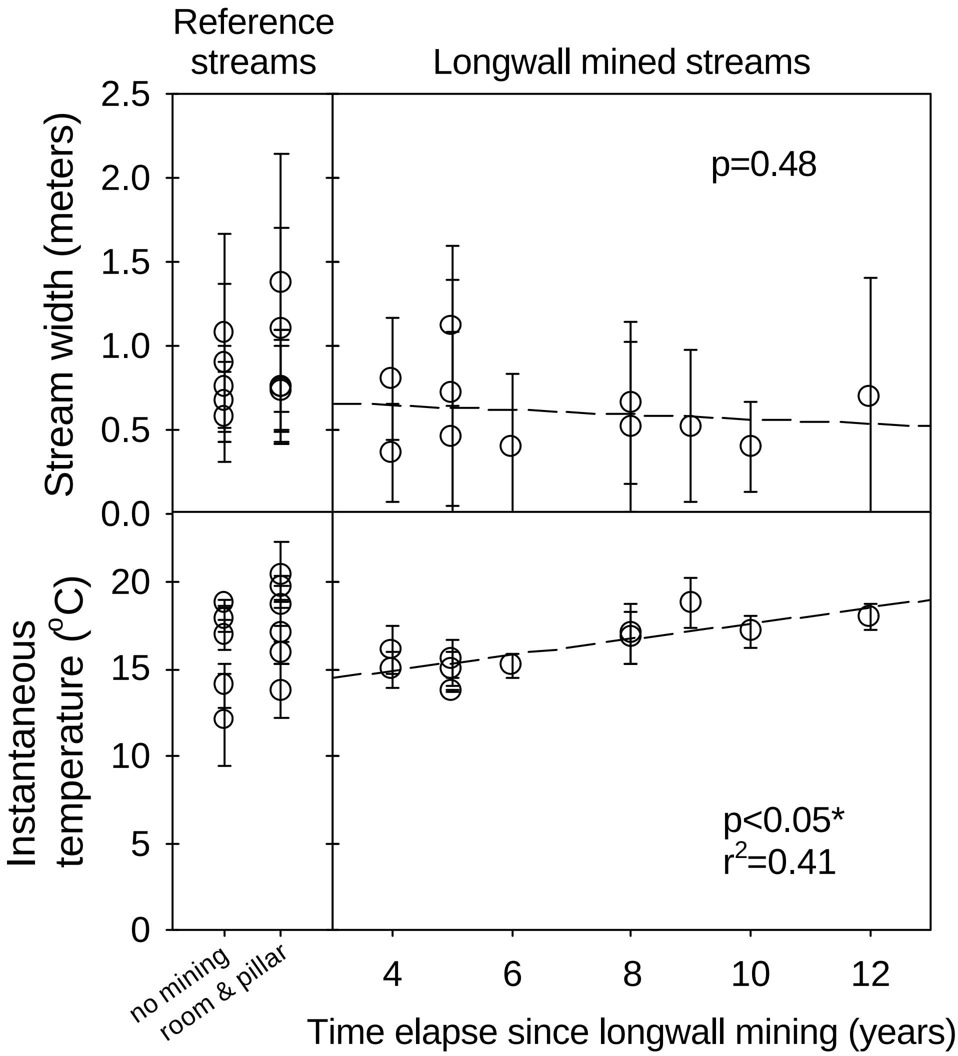


Figure 2. Comparison of mean (and 1 S.D.) physical measurements in reference and longwall mined streams. Trend lines indicate changes in longwall mined streams over time (* indicates trend significantly different than zero).

<u>Average chemical characteristics of study streams</u>

Longwall mined and reference streams were similar in terms of pH and hardness, but statistically different in conductivity, dissolved oxygen, and alkalinity (Table 2). Stream pH ranged from 5.8 to 8.2 in reference and 6.5 to 8.1 in longwall mined streams. Hardness ranged from 54 to 300 in reference streams, and 104 to 240 in disturbed streams. Average pH was 7.65 and average hardness was 177 ppm in all streams.

On average, conductivity was 100 *u*mhos greater in longwall mined streams and alkalinity was 61 ppm greater compared to reference streams. Conductivity ranged from 137 to 582 *u*mhos in reference streams, and 192 to 641 *u*mhos in disturbed streams. Dissolved oxygen saturation averaged 11.4% lower in longwall mined than in reference streams. Dissolved oxygen ranged from 12.9 to 109% saturation in reference streams, and 28.2 to 103.2% saturation in longwall mined streams.

Table 2. Mean (and 1 standard error) chemical characteristics of streams and probability of no significant chemical difference in samples from longwall mined (N=72) versus reference streams (N=79), and (ANOVA, Dunnett's Test ,*p<0.05).

	Reference streams		Longwall mined streams		
Chemical measure	Mean	(SE)	Mean	(SE)	Probability
Ph	7.65	0.04	7.65	0.04	0.955
Conductivity (*u*mhos)	344.8	9.8	444.9	10.2	0.000*
Dissolved oxygen (percent saturation)	86.1	1.9	77.1	2.0	0.010*
Alkalinity (ppm)	134	5	198	5	0.000*
Hardness (ppm)	182	5	172	5	0.150

Chemical characteristics along headwater stream gradients

The pH of headwater streams changed significantly along the stream gradient, but there were no longwall mining induced significant differences in pH along stream gradients (Figure 3). All streams showed a positive increase from pH 7.4 near the source to pH 8.0 in 120 acre watersheds. In contrast, conductivity did not change along stream gradients and longwall mined streams consistently had 100 *u*mhos greater conductivity than reference streams. Alkalinity patterns were similar to conductivity with 64 ppm greater alkalinity in longwall mined streams compared to reference streams along the headwater stream gradient.

Although dissolved oxygen appeared to increase along the stream gradient in both longwall mined and reference streams, any trend was not significantly different than zero (ANOVA, p=0.07) and interaction between the trend lines was not statistically significant (ANOVA, p=0.73). Lack of significant interaction between longwall mined and reference stream dissolved oxygen indicated that longwall mined streams did not achieve reference conditions within the scope of the study.

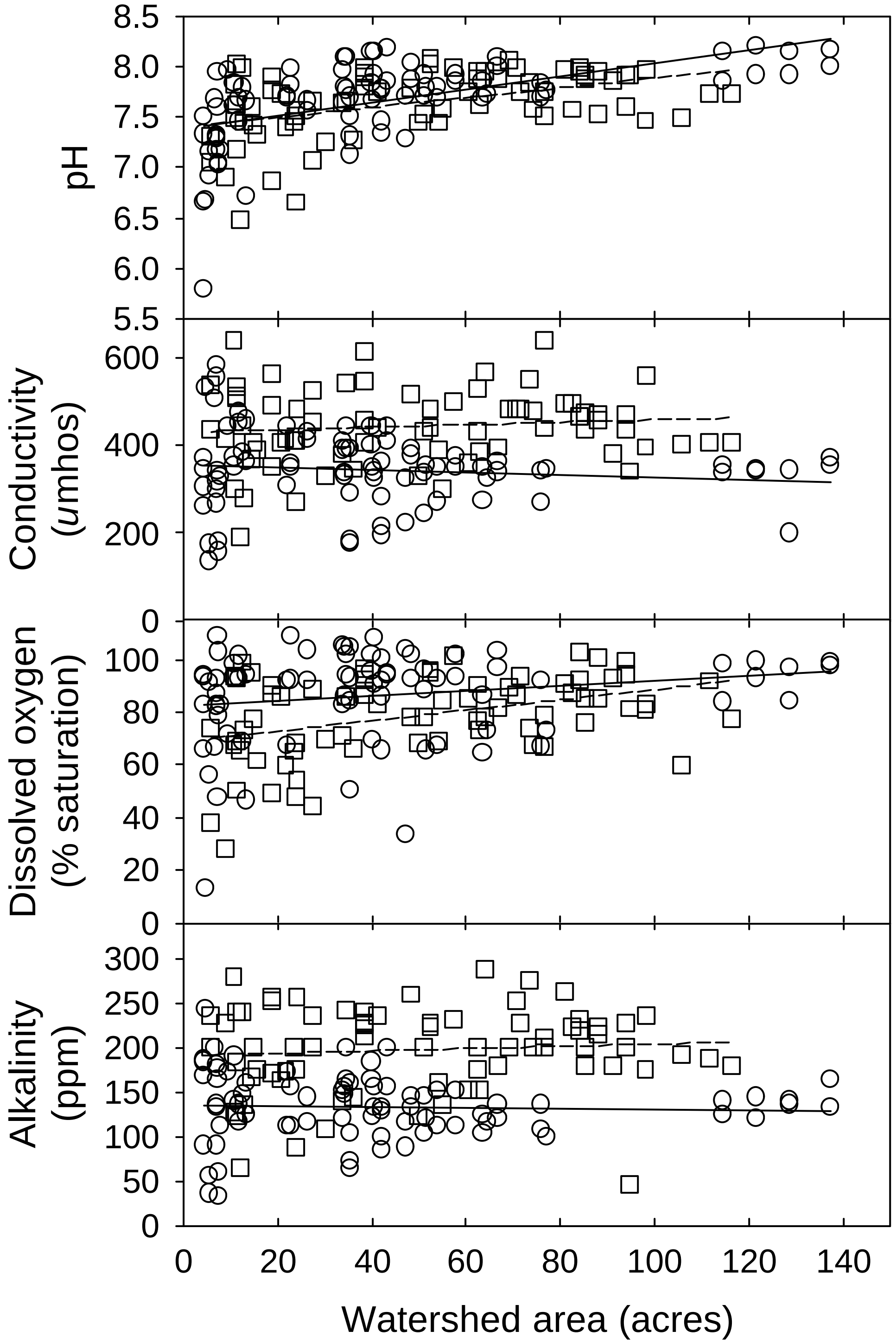


Figure 3. Scatterplots of chemical attributes measured along headwater stream gradients comparing longwall mined (squares) and reference streams (circles). Least square means regression lines for longwall mined (dashed, N=72) and reference (solid, N=79) streams.

Changes in chemical characteristics of longwall mined streams over time

The potential for chemical recovery of longwall mined streams over time was assessed by plotting chemical composition of streams versus time elapsed since mining occurred (Figure 4). Regression analysis was performed to determine if there were any trends in water chemistry in older longwall mined streams versus those that had been mined more recently.

The regression of conductivity over time elapsed since mining was not significantly different than zero, indicating that conductivity did not recover to reference conditions within the twelve years that elapsed since longwall mining occurred in study streams (ANOVA, p=0.19). Since longwall mined streams had an average of 100 *u*mhos greater conductivity than reference streams, it is unlikely that streams could achieve reference conditions over time.

Dissolved oxygen averaged 11% lower saturation in longwall mined streams (Table 2), and recovery to reference conditions was not apparent along the headwater stream gradient (Figure 3). Regression analysis of dissolved oxygen saturation over time elapsed since mining (Figure 4) indicated a downward trend that was significantly different than zero (p=0.02). Therefore, it appears that oxygen levels decrease over time rather than improving to reference conditions. The relationship between alkalinity and time elapsed since mining was not significantly different than zero (p=0.10). It does not appear that alkalinity in streams changes appreciably over twelve-years since mining had occurred in study streams.

Some streams appeared to be less impacted than others, but spatial or temporal recovery to reference water chemistry conditions was not apparent for any of the parameters tested.

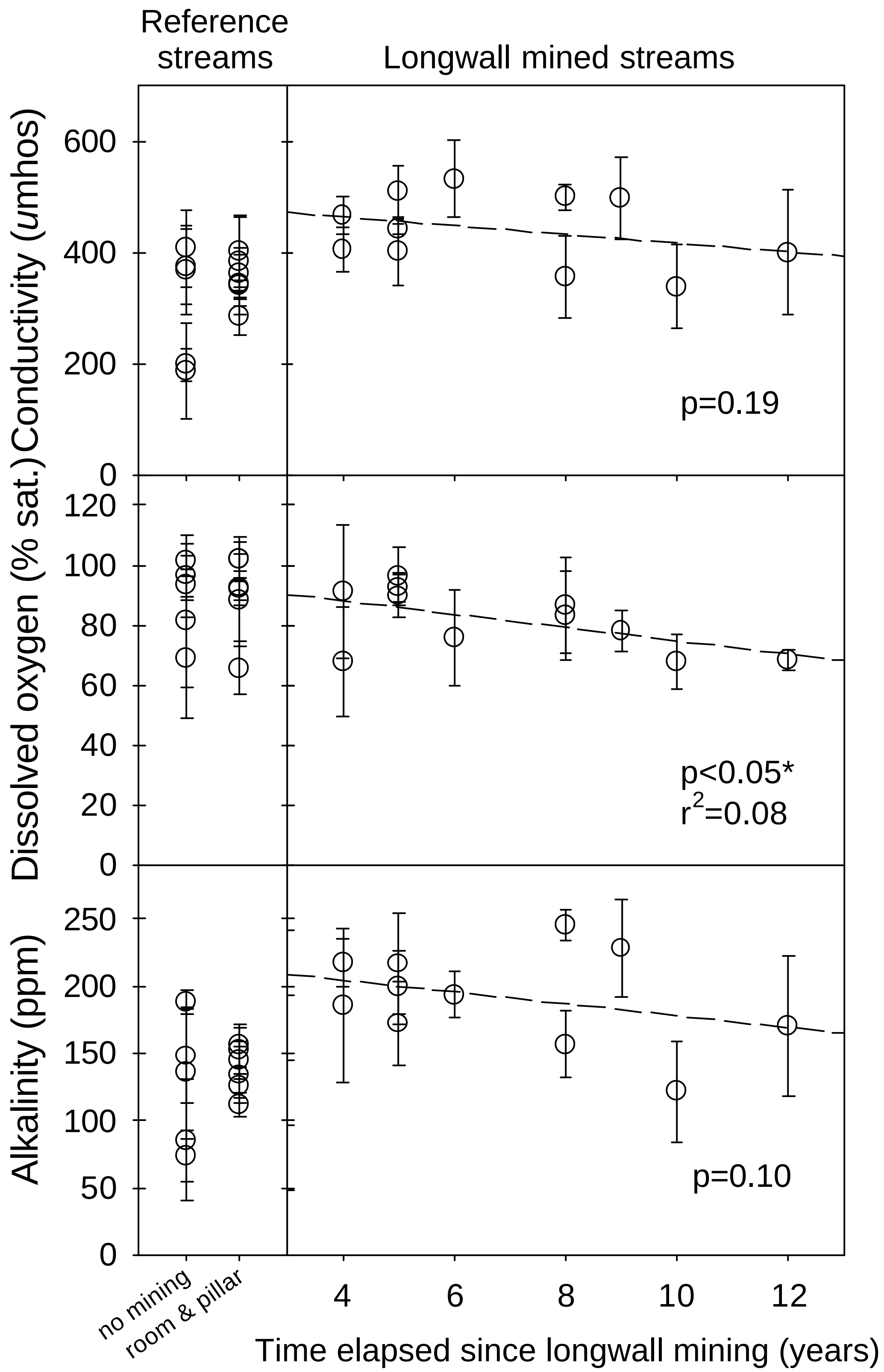


Figure 4. Comparison of mean (and 1 S.D.) chemical measurements in reference and longwall mined streams. Trend lines indicate changes in longwall mined streams over time (* indicates trend significantly different than zero).

Biological characteristics of study streams

Aquatic macroinvertebrate communities were significantly different in all structural dimensions when comparing longwall mined versus reference streams (Table 3). For instance, the probability of no significant difference between the total number of organisms collected in samples from longwall mined versus reference streams was two one-thousandths of a percent, thus the null hypothesis of no significant difference was rejected because it was below the *a priori* threshold of 5% probability. The number of organisms collected in 30-minute composite samples ranged from 3 to 131 in reference streams and 0 to 163 in disturbed streams. On average, 60.4 organisms were collected in reference stream samples and 34.1 organisms were collected in samples from longwall mined streams. Thus, 44% fewer organisms were collected in longwall mined streams. Compared to reference streams, longwall mined streams had 47% fewer kinds of organisms, 49% fewer EPT taxa, and 51% fewer semivoltine taxa. Longwall mining caused mayfly, stonefly, and caddisfly taxa to be reduced by 42%, 52%, and 52% respectively, compared to reference streams.

In general, longwall mining resulted in streams harboring about one-half the abundance and diversity of reference streams. No water was present at 18% of sample sites in longwall mined streams at the time of sampling, therefore, stream communities were impaired at approximately 32% of sites even though water was present at the time of sampling.

Table 3. Mean (and 1 standard error) biological characteristics of streams and probability of no significant biological difference in samples from longwall mined (N=88) versus reference streams (N=79), and (ANOVA, Dunnett's Test ,*p<0.05).

	Reference streams		Longwall mined streams		
Biological measure	Mean	(SE)	Mean	(SE)	Probability
Total number of organisms collected per sample	60.4	3.8	34.1	3.6	0.000*
Taxa richness	12.8	0.6	6.8	0.5	0.000*
EPT taxa	9.0	0.4	4.6	0.4	0.000*
Semivoltine taxa	2.7	0.2	1.3	0.2	0.000*
Mayfly taxa	3.0	0.2	1.7	0.2	0.000*
Stonefly taxa	3.6	0.2	1.7	0.2	0.000*
Caddisfly taxa	2.4	0.2	1.1	0.1	0.000*

Biological characteristics along headwater stream gradients

Biological communities appeared to exhibit greater impacts near the source of longwall mined streams than in downstream reaches (Figure 5). For instance, an average of 10 organisms were collected in samples near the source of longwall mined streams, but 30 organisms were collected in samples where watershed area was greater than 50 acres, and over 60 organisms were collected in samples from longwall mined watersheds that were at least 100 acres. A note of caution: the total number of organisms collected is a measure of relative abundance and is not a measure of how many organisms inhabit the stream.

For the number of organisms collected per sample, both of the main effects were significant (ANOVA, $p<0.05$), including: longwall mined versus reference streams, and distance from the stream source. A significant interaction term ($p=0.02$) indicated a relationship between the main effects. The scatterplot of the total number of organisms collected versus watershed area indicates convergence of longwall mined and reference stream patterns once the watersheds achieved approximately 120 acres in size. Interaction indicates recovery of the relative abundance of macroinvertebrates in downstream reaches of average longwall mined streams. Interestingly, macroinvertebrates were particularly abundant in samples collected from many of the 60 to 100 acre longwall mined streams, whereas macroinvertebrates were absent or nearly absent in many other similar sized longwall mined streams. It is possible that resurgence of water in 60-100 acre longwall mined streams acts as a refuge for a number of macroinvertebrates subjected to dewatering in the upstream reaches.

Diversity in terms of the number of different kinds of macroinvertebrates collected in samples along the headwater stream gradient showed significant main effects in terms of reference versus longwall mined, and distance from the source. Taxa richness did not show significant interaction between main effects ($p=0.49$), indicating the downstream patterns were essentially parallel in longwall mined and reference streams. Therefore, the diversity of macroinvertebrate communities in longwall mined streams failed to recover to reference conditions along the downstream gradient. Spatially, diversity of longwall mined streams did not achieve the diversity of reference streams within the range of the stream size studied. This finding does not rule out the possibility that longwall mined streams may recover to reference conditions in larger, 3^{rd} or 4^{th} order streams outside the scope of this study.

The EPT taxa included mayflies, stoneflies, and caddisflies were significantly impacted by longwall mining (Table 3). The EPT taxa also increased downstream (Figure 5). Lack of a significant interaction ($p=0.26$) indicated that recovery of the longwall mine impacted EPT fauna did not occur within the headwater study streams. Likewise, semivoltine taxa, those that require greater than one year in stream residence to complete their larval stages, did not recover to reference conditions within the spatial dimensions of this study ($p=0.26$). Furthermore, the low numbers of semivoltine taxa in the lower reaches of most longwall mined streams brings into question whether these streams are able to maintain flow conditions necessary for long-lived organisms.

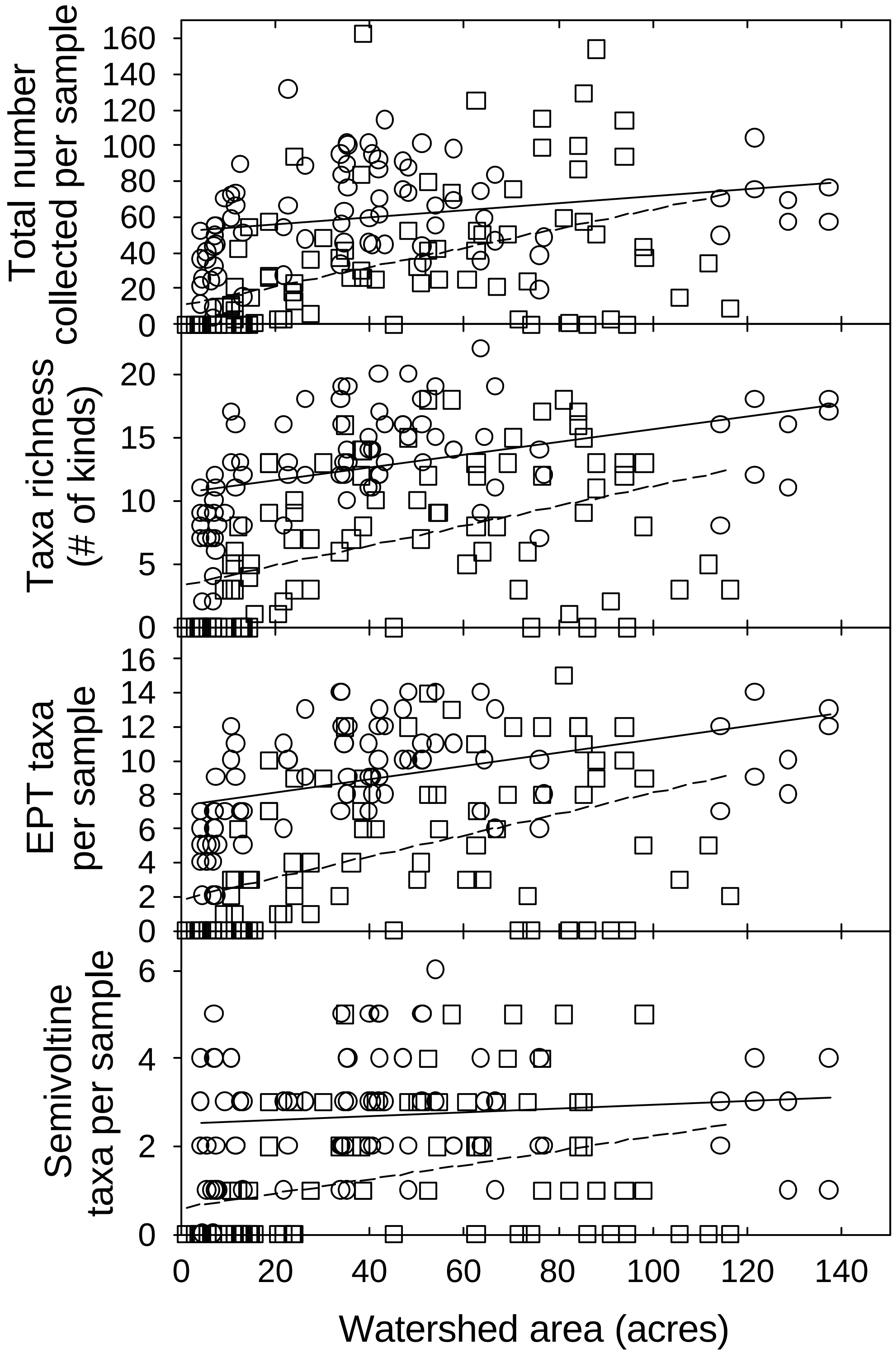


Figure 5. Scatterplots of biological community attributes measured along headwater stream gradients comparing longwall mined (squares) and reference streams (circles). Least square means regression lines for longwall mined (dashed, N=88) and reference (solid, N=79) streams.

In longwall mined streams semivoltine taxa were collected in only 49 of 88, or 56% of samples, whereas reference streams had semivoltine taxa in 76 of 79, or 96% of samples. It was also noted from scatterplots that in many of the samples from 60 to 100 acre longwall mined watersheds where some organisms were collected, semivoltine taxa were absent and EPT taxa were limited in number. In general, EPT taxa have aquatic life histories requiring 9 to 12 months residence.

Biological changes in longwall mined streams over time

The relative abundance, diversity, and longevity of the biological communities in streams did not appear to improve over the twelve-year interval since mining occurred in Marshall County, West Virginia (Figure 6). In regression analysis the number of organisms collected in samples from longwall mined streams was not significantly different over the time elapsed since mining (p=0.17). Likewise, the relationship between taxa richness and time elapsed since mining was not significantly different than zero (p=0.51). The relatively long-lived EPT taxa and the multi-year aquatic semivotine taxa did not respond to any change in condition of streams over the twelve-year period represented by study streams. The structure of the biological communities in longwall mined streams remained essentially unchanged over time. Twelve years after longwall mining, biological communities failed to achieve the abundance, diversity, or longevity of unmined or room-and-pillar mined reference streams.

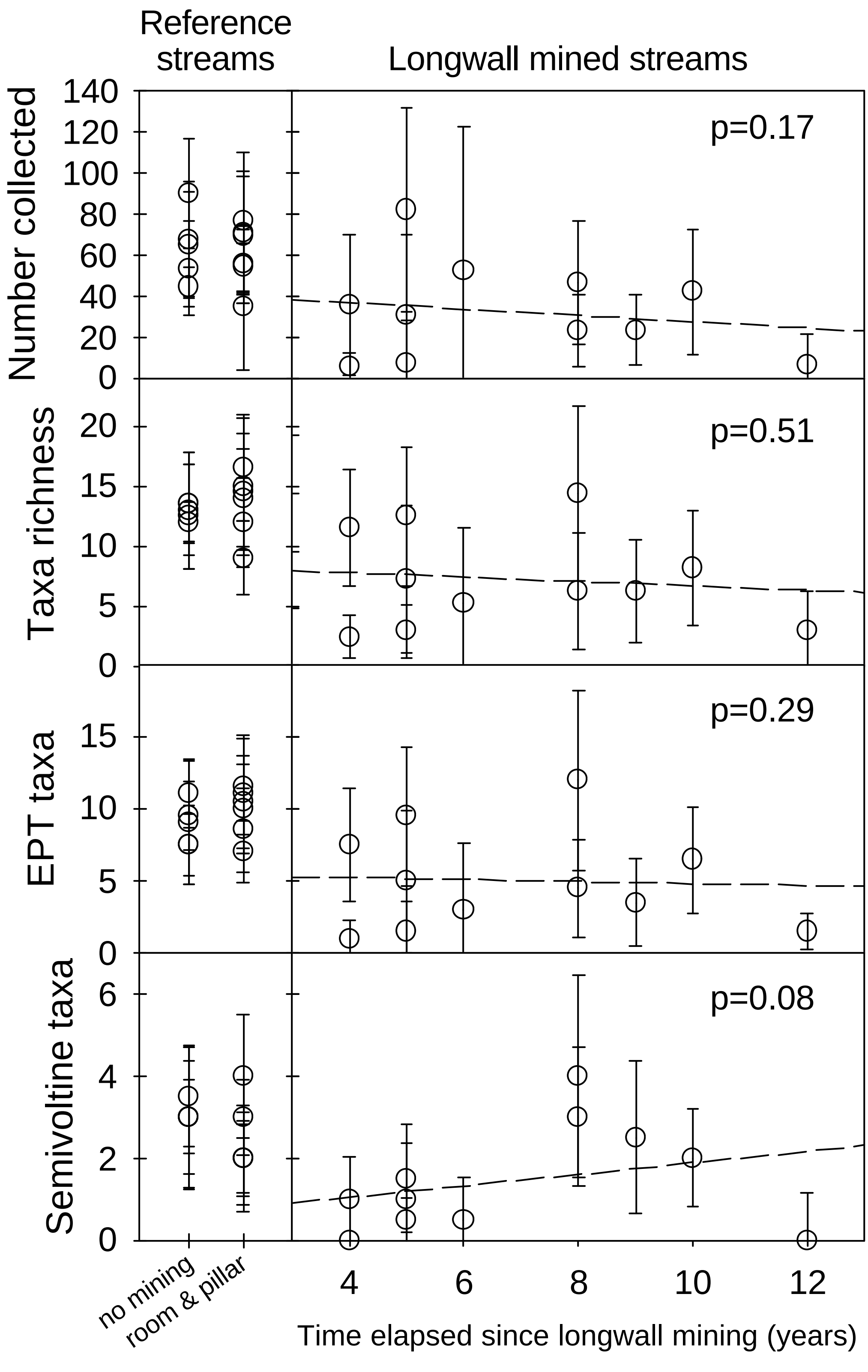


Figure 6. Comparison of mean (and 1 S.D.) biological measurements in reference and longwall mined streams. Trend lines indicate changes in longwall mined streams over time (* indicates trend significantly different than zero).

Community organization and average functional groups in headwater streams

Macroinvertebrate functional feeding groups were assessed for samples where viable communities were present. For functional group analysis at least two individuals (minimum population) from each of two taxa (minimum community) must have been present in a sample. Communities were present in 78 of 79 (99%) reference stream samples and 57 of 88 (65%) longwall mined stream samples. Sixteen samples from longwall mined streams were dry at the time of sampling, and 15 additional samples failed to contain viable communities even though water was present at the time of sampling.

There were no significant differences in the average functional group composition of streams draining longwall mined versus reference watersheds (Table 4). It was noted, however, that average functional group composition for shredders and collectors would be considered different at α=0.10, the 90% probability level. Leaf shredders and fine particle collectors dominated headwater streams in the region. Shredders ranged from 12-80% of the community in reference streams and 0-100% of the community in longwall mined streams. Collectors ranged from 7-84% of the community in reference streams and 0-91% of the community in longwall mined streams. Grazers made up less than 15% of the average community, and predators made up 10-13% of average stream communities.

Table 4. Mean (and 1 standard error) functional group composition of streams and probability of no significant functional difference in samples from longwall mined (N=57) versus reference streams (N=78), and (ANOVA, Dunnett's Test ,*p<0.05).

	Reference streams		Longwall mined streams		
Functional group	Mean	(SE)	Mean	(SE)	Probability
Leaf shredders	39.4%	2.0	34.3%	2.4	0.098
Collectors	34.5%	2.1	40.1%	2.5	0.083
Grazers	12.9%	1.5	15.3%	1.7	0.282
Predators	13.2%	1.2	10.3%	1.4	0.114

Functional group composition along headwater stream gradients

The proportion of leaf shredders in samples declined from greater than 40% near stream sources to approximately 30% in the downstream reaches, a relationship that was significantly different than zero (p<0.05). Whereas there were no significant differences in shredder composition between longwall mined and reference streams, a significant interaction term between the main effect and the gradient effect distance from the source indicated that the pattern of shredder population decline along the stream gradients was significantly different (two-way ANOVA, p<0.05). Notably, scatterplots indicate relatively low shredder populations at the head of some longwall mined streams, and high shredder populations in 50 – 100 acre longwall mined compared to reference streams. This pattern appears to correspond with the resurgence of some longwall mined streams in the lower stream reaches, and may indicate that resurgence areas mimic the spring sources of reference streams in terms of their functional group balance.

Fine particle collectors were 35-40% of the population in streams, with no significant differences between longwall mined and reference streams and no significant pattern of change along the downstream gradient (Figure 7). It was noted that collector proportions were uncharacteristically high in samples from the largest (>100 acre) longwall mined streams, and that shredders were proportionally lower in those samples. Both shredder and collector proportions in samples from longwall mined streams tended to have greater variation from the mean (trend line) than samples from reference streams.

Grazers were not significantly different between longwall mined and reference streams, but the increase in grazer proportions along the downstream gradient was significantly different than zero ($p<0.05$). Grazers increased from about 10% of the community near stream sources to about 20% in the lower reaches. Predators were not significantly different in longwall mined versus reference streams, and remained a constant 10-15% of the communities along stream gradients.

<u>Functional changes in longwall mined streams over time</u>

Although functional group composition of communities was not impacted by longwall mining, there were some changes over time in the functional composition of longwall mined streams (Figure 8). For instance, fine particle collectors declined ($p<0.05$, $r^2=0.12$) and predators increased ($p<0.05$, $r^2=0.21$) over time elapsed since longwall mining occurred in streams. Leaf shredder and algal grazer proportions appeared to remain constant in stream communities regardless of the amount of time that had elapsed since longwall mining had occurred. It was noted that collector proportions declined from nearly 60% of the community in recently mined streams to 20-30% of communities in streams that had been mined 8 to 12 years prior to sampling. Since reference streams had about 35% collectors, the downward shift may signify that macroinvertebrate communities tended to come more into trophic balance a decade after longwall mining. Likewise, predators were nearly absent from recently mined streams but achieved 10-20% of the community in streams mined nearly a decade prior to sampling. Predator proportion in older-aged longwall mined streams compares more favorably with the 13% proportion measured in average reference streams.

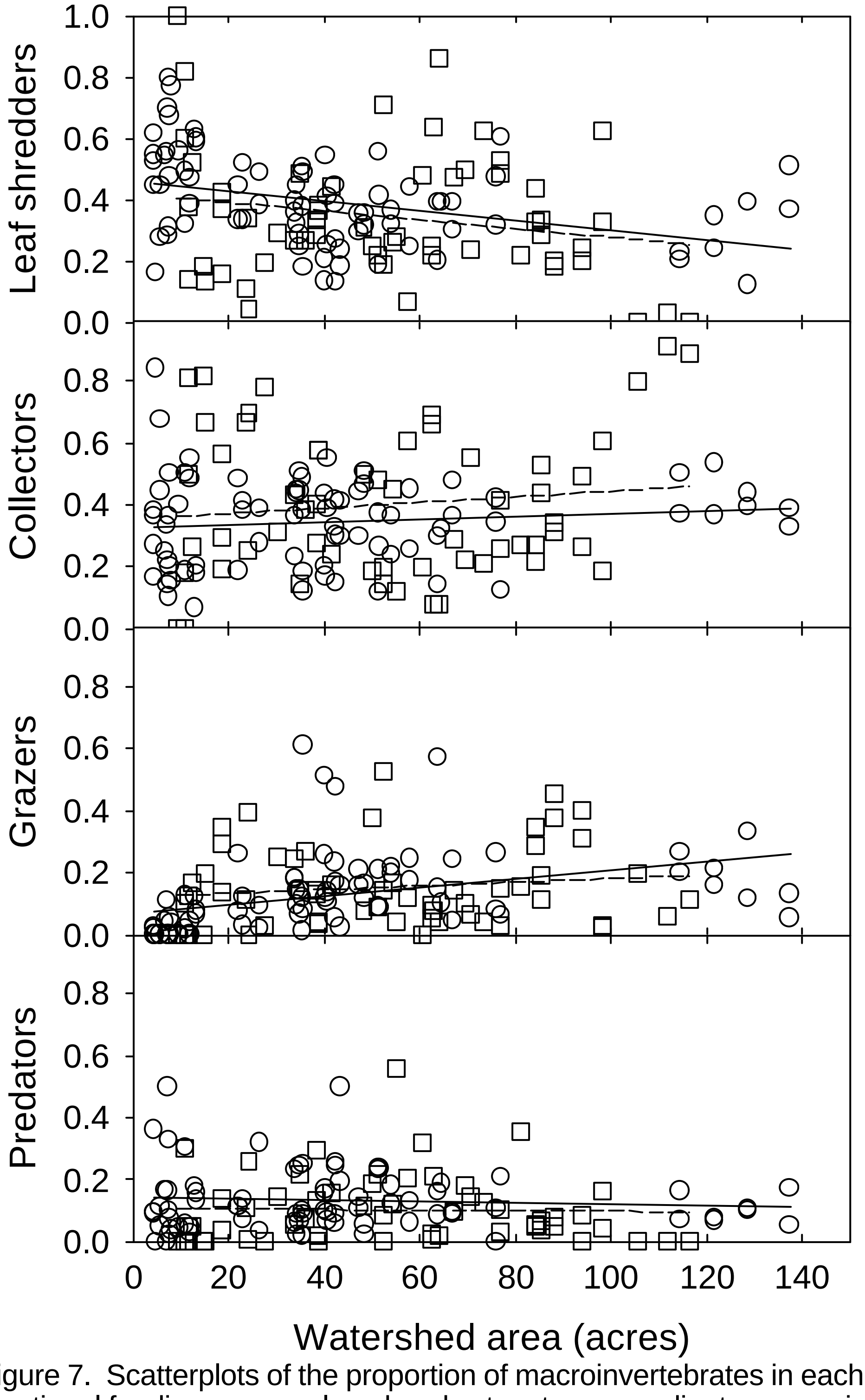


Figure 7. Scatterplots of the proportion of macroinvertebrates in each of four functional feeding groups along headwater stream gradients comparing longwall mined (squares) and reference streams (circles). Least square means regression lines for longwall mined (dashed, N=57) and reference (solid, N=78) streams.

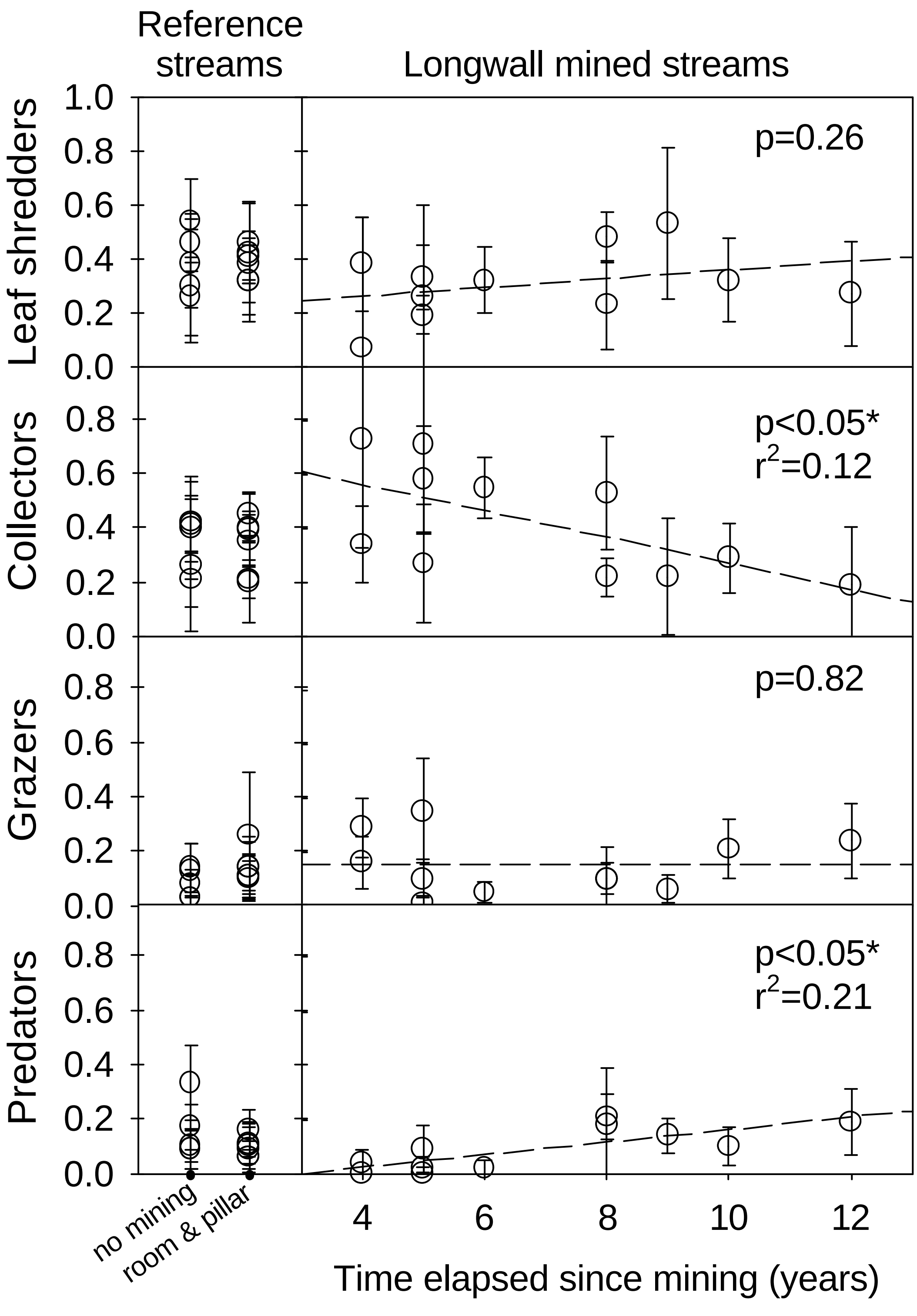


Figure 8. Comparison of mean (and 1 S.D.) functional group composition in reference and longwall mined streams. Trend lines indicate changes in longwall mined streams over time (* indicates trend significantly different than zero).
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Table 5. Taxa collected in order of abundance during the study showing taxonomic affiliations, life cycle (univoltine=completes life cycle in 1 year, and semivoltine=two-year or longer aquatic larval development period), and functional feeding group assignment.

class or insect order	*Genus (species)*	life cycle	Function
Ephemeroptera	*Paraleptaphlebia*	Univoltine	Predator
Plecoptera	*Leuctra*	Univoltine	Shredder
Trichoptera	*Diplectrona*	Univoltine	Collector
Plecoptera	*Agnetina*	Semivoltine	Predator
Ephemeroptera	*Heptagenia*	Univoltine	Grazer
Plecoptera	*Peltoperla*	Semivoltine	Shredder
Decopoda	*Cambarus*	Semivoltine	Shredder
Plecoptera	*Amphinemura delosa*	Univoltine	Shredder
Trichoptera	*Neophylax*	Univoltine	Grazer
Ephemeroptera	*Stenonema*	Semivoltine	Grazer
Amphipoda	*Gammarus*	Univoltine	Shredder
Trichoptera	*Lepidostoma*	Univoltine	Shredder
Ephemeroptera	*Baetis*	Univoltine	Collector
Trichoptera	*Pycnopsyche*	Univoltine	Shredder
Megaoptera	*Nigronia serricornis*	Semivoltine	Predator
Isopoda	*Isopoda*	Univoltine	Shredder
Plecoptera	*Acroneuria carolinensis*	Semivoltine	Predator
Diptera	*Dicronota*	Univoltine	Predator
Diptera	*Dixa*	Univoltine	Collector
Plecoptera	*Isoperla*	Univoltine	Predator
Plecoptera	*Perlesta*	Semivoltine	Predator
Diptera	Chironomidae	Univoltine	Collector
Plecoptera	*Ostracerca*	Univoltine	Shredder
Ephemeroptera	*Ameletus*	Univoltine	Collector
Diptera	*Limnophora*	Univoltine	Collector
Diptera	*Tipula*	Univoltine	Shredder
Coleoptera	*Dubiraphia*	Univoltine	Collector
Plecoptera	*Sweltsa*	Semivoltine	Shredder
Trichoptera	*Polycentropus*	Univoltine	Collector
Ephemeroptera	*Epeorus*	Univoltine	Grazer
Trichoptera	*Cyrnellus*	Univoltine	Collector
Trichoptera	*Rhyacophila*	Univoltine	Predator

Table 5 (cont.). Taxa collected in order of abundance during the study showing taxonomic affiliations, life cycle (univoltine=completes life cycle in 1 year, and semivoltine=two year or longer aquatic larval development period), and functional feeding group assignment.

class or insect order	*Genus (species)*	life cycle	Function
Diptera	*Hexatoma*	Univoltine	Predator
Annelida	*Oligochaeta*	Univoltine	Collector
Ephemeroptera	*Ephemera*	Semivoltine	Collector
Ephemeroptera	*Eurylophella temporalis*	Univoltine	Collector
Molluska	*Gastropoda*	Univoltine	Grazer
Coleoptera	*Dytiscus*	Univoltine	Predator
Trichoptera	*Wormaldia*	Univoltine	Collector
Odonata	*Cordulegaster*	Semivoltine	Predator
Diptera	*Eubriidae*	Univoltine	Predator
Megaloptera	*Sialis*	Univoltine	Predator
Trichoptera	*Dolophilodes*	Univoltine	Collector
Diptera	*Hydroporinae*	Univoltine	Collector
Diptera	*Ormosia*	Univoltine	Collector
Odonata	*Calopteryx*	Semivoltine	Predator
Odonata	*Stylogomhus*	Semivoltine	Predator
Diptera	*Hydrocantus*	Univoltine	Predator
Diptera	*Stratiomys*	Univoltine	Predator
Molluska	*Bivalvia*	Univoltine	Collector
Plecoptera	*Clioperla clio*	Univoltine	Predator
Trichoptera	*Hydropsyche betteni*	Univoltine	Collector
Odonata	*Aeshna*	Univoltine	Predator
Coleoptera	*Dytiscidae*	Univoltine	Predator
Diptera	*Helochares*	Univoltine	Collector
Diptera	*Hydroptilidae*	Univoltine	Collector
Coleoptera	*Psephenus*	Univoltine	Grazer
Diptera	*Limnophila*	Univoltine	Predator
Diptera	*Simulium*	Univoltine	Collector
Diptera	*Tabanus*	Univoltine	Predator
Corixidae	*Corixa*	Univoltine	Predator

Discussion

The physical dimensions of the reference and longwall mined watersheds were comparable with the exception of stream width and water temperature. Longwall mined streams were dry at 18% of study sites, most of which were within 150m of the point of flow origin. Frequent dewatering of streams near their sources is consistent with the findings of Leavitt & Gibbens (1992) and Johnson (1992) that upland wells in the Pittsburgh seam are more likely to drawdown than wells in valley bottoms. All longwall mined streams appeared to re-emerge at some point downstream of the source, but re-emergence was not sufficient for full recovery of stream width for many of the longwall mined streams. Resurgence of some streams but not others is consistent with the variable responses measured in aquifers overlaying Pennsylvanian coal in Illinois (Booth, 2002) and West Virginia (Cifelli & Rauch, 1986; Tieman & Rauch, 1987). Fractured aquitards causes water to drain from upper-level aquifers to lower-level aquifers. Resurgence of streams depends on the connection of lower-level aquifers to recharge zones and the ability of aquifers to transmit water back into the stream bed (Booth, 2002).

Instantaneous water temperature averaged 0.8^{o}C lower in longwall mined streams and remained consistently lower than temperatures in reference streams along the headwater stream gradient. As watersheds achieved 100 acres in size, summer daytime water temperatures were 1–2^{o}C lower in longwall mined streams than in reference streams. Lower stream temperature appeared to be related to loss of water at the surface and longer underground residence time. This was further evidenced by water temperatures being less variable in longwall mined than in reference streams.

Three of five chemical measures showed significant differences when comparing longwall mined versus reference streams. Higher total dissolved solids and alkalinity have been reported previously in longwall impacted groundwater in Pennsylvanian coal (Booth & Bertsch, 1999; Rauch, 1989). Stream water quality appeared degraded as evidenced by higher conductivity in longwall mined streams. However, the presence of carbonate minerals in fractured rock strata helped buffer the dissolution of pyritic materials, thus pH remained similar to reference conditions. Compared to reference conditions, lower dissolved oxygen concentrations may be in part due to higher chemical oxygen demand, and in part due to lower atmospheric contact in subsided longwall mined streams.

Within the biological community the EPT Taxa represented 28 of the 60 kinds of macroinvertebrates collected, and 83% total number of macroinvertebrates collected in this study. One can expect to collect between 6 and 14 different EPT Taxa at any site in any reference stream 95% of the time. The EPT Taxa are often used as indicators of good water quality because as a group they are particularly responsive to disturbance (Rosenberg & Resh, 1993). In this study the primary interest in EPT Taxa is their relatively long aquatic larval development period. With some exceptions, EPT Taxa typically require greater than nine months residence in streams in order to complete their larval development and successfully emerge as adults (Wallace & Anderson, 1996). The co-existence of multiple EPT Taxa in these streams during summer months is indicative of stream permanence. These streams, often mistakenly referred to as “ephemeral” or “intermittent” because of their inaccurate depiction on USGS 1:24,000 scale data (Meyer, et al, 2003), are indeed perennial landscape elements.

In prior studies the difference in the response of EPT Taxa, with a 29% proportional reduction in ubiquity following longwall mining, versus Semivoltine Taxa, with a 51% proportional reduction in ubiquity, was approximately 22% (Stout, 2003). The dynamic changes in headwater stream communities indicate that 29% of perennial headwater streams are “dewatered,” lasting a few weeks at most following a storm event, sometimes providing isolated pockets of refuge, but incapable of supporting a sustained aquatic community. An additional 22% of longwall mined streams are “partially dewatered,” supporting organisms with up to nine month life cycles but failing to provide suitable conditions for the perennial macroinvertebrate communities observed in reference streams. Longwall mining results in a 50% reduction in the omnipresence of perennial aquatic biological communities in headwater streams across the region.

In this study, there was little evidence of streams recovering from the dewatering effects of longwall mining. Spatially, the number of organisms collected per sample increased in downstream reaches where subsided streams re-emerged into the streambed. However, diversity and longevity of stream communities remained well-below reference conditions in stream reaches downstream of resurgence areas. Temporally, there was no evidence of stream recovery over the twelve-year period of time that had elapsed since longwall mining occurred in Marshall County streams. Lack of temporal recovery appears to be the case in other regions of the world (Holla & Barclay, 2000).

In many regions, headwater streams harbor biodiversity that equals or exceeds that of larger downstream reaches (Feminella, 1996; Dieterich & Anderson, 2000; Williams, 1996). Many species live only in headwater streams, and loss of headwaters represents a significant threat to southern Appalachian fauna (Morse *et al*, 1993). In study streams the seal, longtail, two-lined, and spring salamanders dominated the obligate aquatic amphibian community, but many other amphibians in this region depend on headwater streams as breeding sites (Green & Pauley, 1987).

Headwater streams provide critical services to consumers in the surrounding forest and in downstream reaches. Headwater communities convert imported low quality forest products such as leaves and sticks into high quality products in the form of insect tissue. Primarily fats and protein, insects emerge from streams in a form that is consumable by a plethora of forest species at a time that coincides with breeding a rearing of subsequent generations. By-products, in the form of insect frass, are exported downstream where they become a resource of a host of invertebrates that filter the water column and eventually contribute to higher trophic levels. Headwater streams are functionally critical landscape elements and the loss of one-half of all headwater streams to longwall mining could have significant consequences for the health of central Appalachian forest ecosystems.

Conclusion

Aquatic macroinvertebrate communities in reference streams are ubiquitous across the region, rich in diversity, long-lived, and dependent on the surrounding terrestrial ecosystem for energy and nutrients. Longwall mining resulted in a net loss of approximately one-half of all headwater streams in Marshall County, West Virginia. Streams were particularly impacted near the source, and most re-emerged downstream. Macorinvertebrate abundance appeared to recover to reference conditions in the lower reaches of longwall mined streams. However, neither diversity or longevity of the macroinvertebrate community recovered along the stream gradient. There was no indication that the physical, chemical, or biological impacts of longwall mined streams recover over time.

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