

Stream functional response to mountaintop removal and valley fill coal mining

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ABSTRACT

Mountaintop removal and valley fill (MTRVF) mining has become a widespread means of coal extraction in the central Appalachians. During MTRVF several hundred meters of overburden are removed to access coal seams, and excess rubble is dumped into adjoining valleys and streams. Filling valleys eliminates stream headwaters and may result in loss of stream ecosystem functions, which are dependent on temporal and lateral connectivity in river networks. To determine the affect of MTRVF on stream ecosystem function, leaf breakdown, which is an ecosystem level attribute of forested streams, was measured in five streams draining MTRVF sites and five reference streams in central West Virginia. Leaf packs of white oak and red maple were installed in these streams in December 2007, leaves were collected in January, February, March, April, and June of 2008, and leaves were washed and processed in the lab. Leaf breakdown rates were significantly slower in filled streams. MTRVF streams were marked by high sediment levels, elevated base flow, elevated conductivity and pH, and a lower density and richness of shredding macroinvertebrates than reference sites, suggesting that slower leaf decay was the result of the combined set of altered conditions in MTRVF streams. Additionally, MTRVF streams showed no species-level difference between red maple and white oak breakdown rates, indicating that MTRVF inhibits control of ecosystem function exerted by leaf species characteristics.

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Introduction:

Mountaintop removal and valley fill mining (MTRVF) is a widely used means of coal extraction in the Central Appalachians. During MTRVF hill slopes are clear cut, several hundred meters of overburden are blasted to access shallow coal seams, and excess rubble is dumped into adjoining valleys and streams. Remediation for MTRVF generally consists of grading rubble, planting it with non-native grasses, and installing rock-lined drainage channels down the center of the fill that drain into settlement ponds. Pond water quality is amended and a series of silt curtains control the amount of sediment entering the original stream channel from the pond.

MTRVF has resulted in the filling of 724 miles of streams from 1985 to 2001, and more than 1,200 miles of headwater streams and their watersheds were impacted by MTRVF between 1992 and 2002 (Phillips 2003; EPA EIS 2005). Headwater streams, defined as all first and second order streams, regardless of permanence of flow (Freeman et al. 2007), compose approximately 85% of total channel length in a typical river network (Leopold 1964). Low-order streams are locations of nutrient processing and retention (Sweeney et al. 2004; Roberts et al. 2007), regulation of hydrology (Freeman et al. 2007), and energy processing and transport (Vannote et al. 1980; Freeman et al. 2007) for lower reaches of river networks. Additionally, headwaters provide an interface between terrestrial landscapes and riverine systems (Cummins and Klug 1979; Gomi et al. 2002; Pringle 2003), where terrestrial vegetation contributes energy in the form of coarse and fine particulate organic matter (Cummins and Klug 1979; Vannote et al. 1980). Lower reaches of river networks also depend on headwaters for macroinvertebrate

colonization through drift (Anholt 1995) and serve as a source of biological diversity (Meyer et al. 2007).

Coarse particulate organic matter (CPOM) and fine particulate organic matter (FPOM) are predominately generated from the processing of dead leaves, the major source of energy for Appalachian headwater streams (Minshall 1967; Petersen and Cummins 1974; Wallace et al. 1997). Leaf processing is progression of steps which begins with the leaching of soluble materials, followed by colonization by microorganisms, and completed by the consumption and physical breakdown of leaves by shredding macroinvertebrates (shredders) and abrasion due to the physical processes of streams (Petersen and Cummins 1974). Rates of leaf breakdown are influenced by the species level characteristics of leaves (Ostrofosky 1997; Swan and Palmer 2004; Lecerf and Chauvet 2008), the type (Jonsson and Malmquist 2003; Hury et al. 2002) and density (Cuffney et al. 1990) of the shredders, and chemical and physical characteristics of the stream, such as temperature (Webster and Benfield 1986), dissolved nutrient concentration (Meyer and Johnson 1983), sediment (Herbst 1980; Naamane et al. 1999), and discharge (Webster and Benfield 1986).

Leaf breakdown is an ecosystem level functional attribute of forested streams and, as such, has been used to investigate disturbance effects on stream function because it incorporates multiple levels of organization into one metric (Sponseller and Benfield 2001; Gessner and Chauvet 2002; Young et al. 2008). For example, leaf breakdown has been used to examine the impacts of urbanization (Meyer et al. 2005), agriculture (Doledec et al. 2006), logging (Benfield et al. 2001) and mining (Gray and Ward 1983; Maltby and Booth 1991; Niyogi et al. 2001; Simmons et al. 2008). While multiple

confounding factors make the results of leaf breakdown studies complex (Chadwick et al. 2006; Hagan et al. 2006), studies of ecosystem function provide more complete insight into the nature of the impacts of land use disturbance on stream integrity and persistence (Bunn et al. 1999; Gessner and Chauvet 2002; Young et al. 2008).

We examined leaf breakdown as a measure of ecosystem function in stream channels directly downstream of valley fills. Previous work has shown MTRVF alters physical and chemical attributes of streams, such as hydrology and water chemistry (Phillips 2003; Wiley and Brogan 2003). Because of the disconnection of the stream channel from its headwaters and the loss of riparian vegetation upstream, thereby altering stream temperature, hydrology, and water chemistry, we predicted that lower reaches would process organic matter less efficiently than reference streams. MTRVF results in impaired macroinvertebrate communities (Hartman et al. 2005; Pond et al. 2008), thereby reducing the mechanical reduction of CPOM by leaf shredders. Additionally, surface mining, like MTRVF, inhibits microbial communities, which are responsible for leaf conditioning, (Gray and Ward 1983; Maltby and Booth 1991; Niyogi et al. 2001), thus we expected a slowing of leaf breakdown rates.

Methods:

Sites:

Leaf breakdown was assessed at five headwater streams downstream of MTRVF activity and five reference headwater streams in the Twenty Mile Creek watershed (lat 38.3°N, long 81.1°W) in central West Virginia. The MTRVF streams (Lost Creek, Sugarcamp Branch, Beech Creek, Hardaway Branch and Buckles Branch) consisted of natural stream channels draining filled watersheds and were bordered by mature riparian

vegetation. Fills were planted with exotic grasses upstream of study reaches, but riparian tree composition was fairly similar among streams and included eastern hemlock (*Tsuga canadensis*), tulip poplar (*Liriodendron tulipifera*), sweetgum (*Liquidambar styraciflua*), red oak (*Quercus rubra*) and sycamore (*Platanus occidentalis*). All MTRVF study reaches were downstream of treatment ponds, except Lost Creek, where there was not sufficient stream length between the pond and the stream's confluence with Twenty Mile Creek to permit leaf pack installation.

Reference streams (Laurel Creek, Ash Creek, Neil's Branch, Jack's Fork and Peter's Branch) had no upstream valley fills, but all showed evidence of past disturbance from logging, road construction, and installation and presence of natural gas wells. Riparian vegetation was similar to that of MTRVF sites. All ten study streams were low order, high gradient, had similar stream bed structure, and drained similarly sized watersheds (Table 1).

Table 1. Physical characteristics of watersheds

<i>Stream</i>	<i>Watershed area (km²)</i>	<i>Riparian zone length (km)</i>	<i>% Forest</i>	<i>% Barren land</i>	<i>% Channel filled</i>
Ash (Ref)	3.99	5.9	100.0	0.0	0.0
Jacks (Ref)	0.91	1.3	99.7	0.0	0.0
Laurel (Ref)	1.41	1.6	100.0	0.0	0.0
Neil (Ref)	3.73	5.5	99.8	0.1	0.0
Peters (Ref)	1.62	2.8	94.7	0.1	0.0
Beech (MTRVF)	0.57	0.3	36.1	63.9	56.0
Buckles (MTRVF)	2.61	2.6	61.9	38.1	30.0
Hardaway (MTRVF)	1.43	1.5	40.6	59.4	40.0
Lost (MTRVF)	0.78	0.2	8.1	91.9	85.0
Sugarcamp (MTRVF)	5.27	2.4	18.9	77.4	68.0

Leaf Breakdown:

We installed 60 leaf packs containing either 5.0 grams of naturally senesced red maple (*Acer rubrum*) leaves or 5.5 grams of white oak (*Quercus alba*) in coarse mesh (1 cm) “grape” bags over approximately 200 meter reaches in each stream. Leaf packs were attached to nylon string in sets of five, and six strings of each species were attached to wire loops anchored to roots or trees on stream banks. Leaf packs were then secured by large rocks to prevent tangling. One leaf pack per string (n = 5 leaf packs of each leaf species per stream) was removed after 21, 55, 91, 115, and 180 days, placed in Ziploc® bags, transported to the laboratory and refrigerated until processed. Leaves were washed over nested 2mm and 0.25mm mesh sieves, and leaf particles larger ca. 20mm were placed in paper sacks to air dry for five days. Samples were then dried in a warming oven at 50° C for at least 24 hours to a constant weight, weighed to obtain dry mass, ground in a Wiley Mill, and a one gram sub-samples of ground material were combusted at 550° C for one hour to obtain AFDM. Breakdown rates (k-values) were determined by regressing the natural log of the percent organic matter remaining against leaf incubation time in streams (Webster and Benfield 1986) using a total of 30 leaf packs per species per stream.

Macroinvertebrates:

Macroinvertebrates were removed from leaf packs, preserved in 80% ethanol, and shredders were identified to genus using Merritt and Cummins (1996) and other taxon-specific keys, and counted. Shredder density was determined as the number of individuals per leaf pack (n = per leaf species, per stream, per date).

Sediment accumulation in leaf packs:

Fine and coarse sediments accumulating on leaf packs were collected in April. Sediments were quantified following Golladay et al. (1989). Coarse sediments (2mm to 0.25 mm), were collected, air dried for one week, dried at 50° C for at least 48 hours, and combusted at 550° C for 1.5 hours to determine AFDM. Fine sediment (<0.25mm) was transferred to a 5 L bucket containing tap water, homogenized by stirring, and three 50ml samples were taken for each leaf pack. Samples, corrected for bucket volume, were filtered through pre-ashed 47mm glass fiber filters, dried, ashed and weighed to determine the mass of inorganic sediment per leaf pack.

Fungal Biomass:

Ergosterol was used to quantify fungal biomass, following an adaptation of Gulis and Suberkropp (2006). Ten disks were punched from each leaf species per stream per month using a 1cm diameter cork borer, except for June samples, because there was insufficient leaf mass remaining to permit measurement. Five leaf disks were stored in 5ml of methanol at -20°C until processing. The remaining five leaf disks were dried at 50°C for 24 hours, weighed, and combusted at 550° C for one hour to determine AFDM.

Samples stored in methanol were then brought to room temperature and refluxed in a dry bath at 70°C with methanol and KOH for approximately one hour. Samples were then centrifuged and pellets discarded. Extracted ergosterol was dissolved into pentane using a series of liquid-liquid extractions and the pentane allowed to evaporate overnight in a fume hood. Ergosterol was then re-dissolved in methanol and filtered through 0.2µm nylon filters. Ergosterol was quantified using a high performance liquid chromatograph (HPLC).

Statistical Analysis:

Differences in leaf breakdown rates (k-values) were assessed using a full factorial two-way ANOVA design in which stream type (MTRVF or reference) and leaf species were treated as main effects and the interaction of stream type and leaf species were tested by crossing these variables. Fine and coarse sediment accumulations were tested using the same two-way model as that used for leaf breakdown rates. In order to allow for the influence of natural variance of organic matter remaining in leaf packs, a three-way ANOVA was used to test the influence of stream type, time, and leaf species, and the interactions of each of these variables, on organic matter remaining. Time was treated as a categorical variable for statistical analyses because pick-up dates for leaf packs were uniform among all streams and determined a priori. Fungal biomass and shredding macroinvertebrate density per leaf pack were examined using the same three-way ANOVA. All analyses were run using SAS 9.1 and JMP 7.1 (SAS Institute, Cary, North Carolina).

To identify environmental and biological variables related to leaf breakdown rates, a principle component analysis was run in Minitab 15 (Minitab, Inc. State College, Pennsylvania). Variables with scores from the first two primary axes that were highly correlated with breakdown rates were then regressed against breakdown rates using SigmaStat 3.5 (Systat Software, Inc., Chicago, Illinois). Conductivity, background ammonium, pH, fine sediment accumulation, coarse sediment accumulation, macroinvertebrate density, and fungal biomass were used to analyze breakdown rates. Fine and coarse sediment accumulations were summed for each leaf species by stream to produce one fine and one coarse sediment value for each stream, and these numbers were

then regressed against the percentage of stream channel filled in each watershed.

Differences in watershed characteristics and water quality were determined using t-tests.

If distributions were not normal, a Mann-Whitney ranked sum t-test was used.

Results:

Physical and chemical variables:

Discharge was higher in MTRVF streams (Figure 1) than reference streams ($p = 0.016$), even during the drought conditions present during October 2007. When discharge was standardized by watershed area (Figure 2), a sharp distinction between MTRVF and reference streams appeared ($p = 0.013$), and MTRVF streams had approximately 1.5 times higher discharge per square kilometer than did reference watersheds. Wetted width of stream channels ($p = 0.89$) and water temperature ($p = 0.63$) were fairly similar between stream type. Average ammonium concentrations were higher in MTRVF streams than reference streams ($p = 0.095$), due mainly to high concentrations in one stream. Conductivity was significantly elevated in MTRVF relative to reference streams ($p = 0.008$), and, at some locations, as much as 70 times than the specific conductance in reference streams. MTRVF streams had a consistently higher pH (7.0-8.4) than reference streams (6.16.7) ($p < 0.001$).

Figure 1. Mean (± 1 SE) physical and chemical characteristics of reference and MTRVF streams. A is wetted width, b discharge, c pH, d specific conductance, e temperature, and f ammonium concentration.

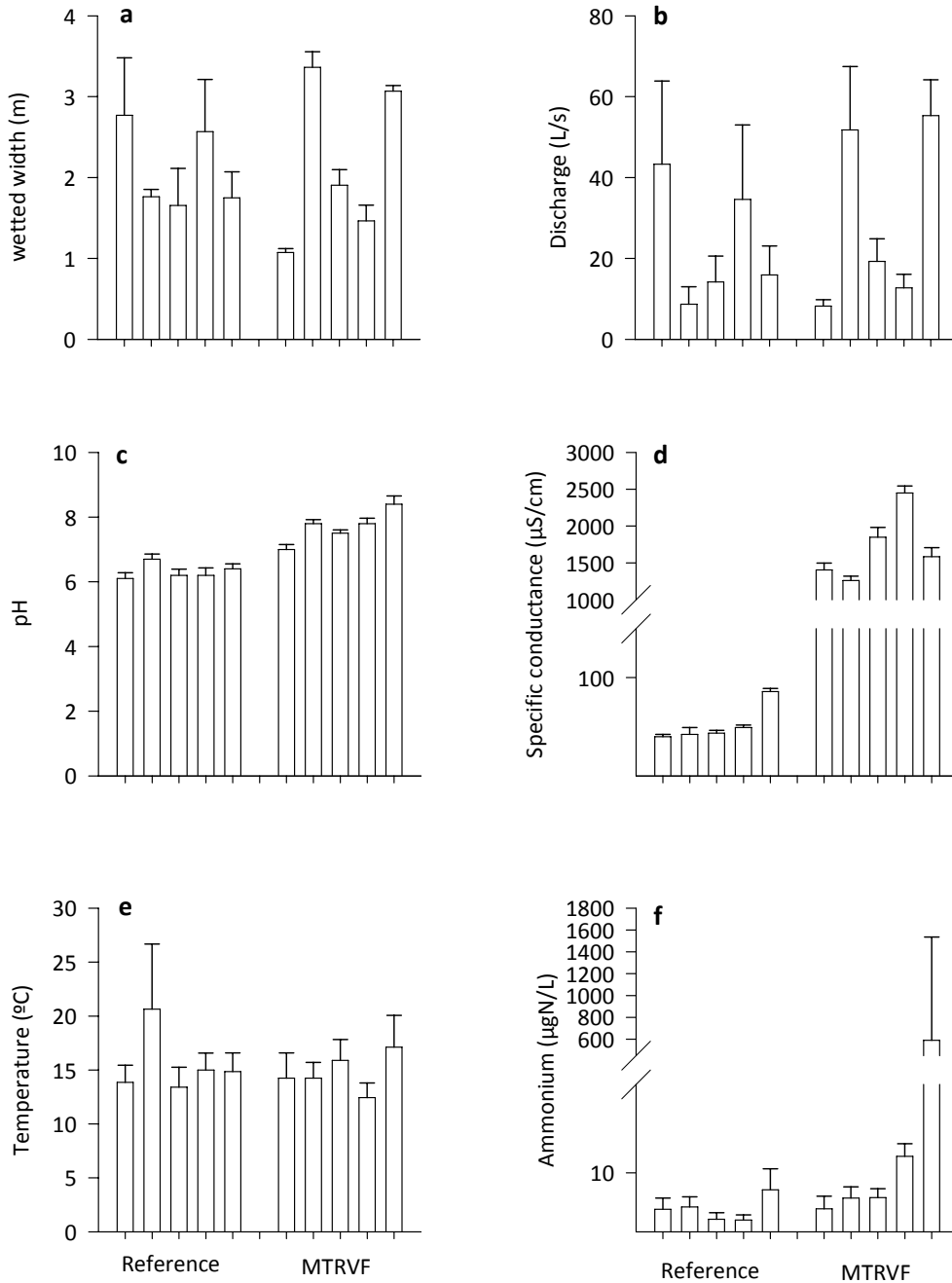
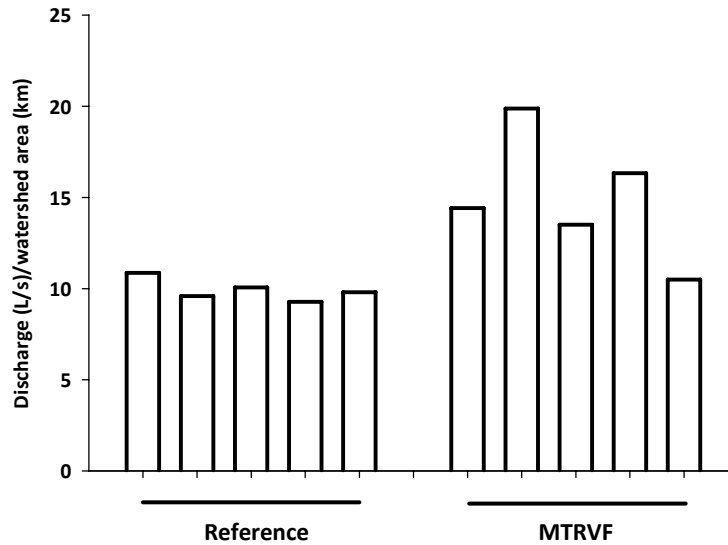


Figure 2. Discharge standardized by watershed area



Leaf breakdown:

Breakdown rates were faster in reference streams (ANOVA, $p = 0.043$) than MTRVF streams (Figure 3). There were no leaf species differences in breakdown rate (ANOVA, $p = 0.13$). Breakdown rates in MTRVF streams appeared similar for both leaf species (Figure 4), but breakdown rates in reference streams tended to follow a species-specific pattern.

Figure 3. Mean (± 1 SE) breakdown rates by stream type.

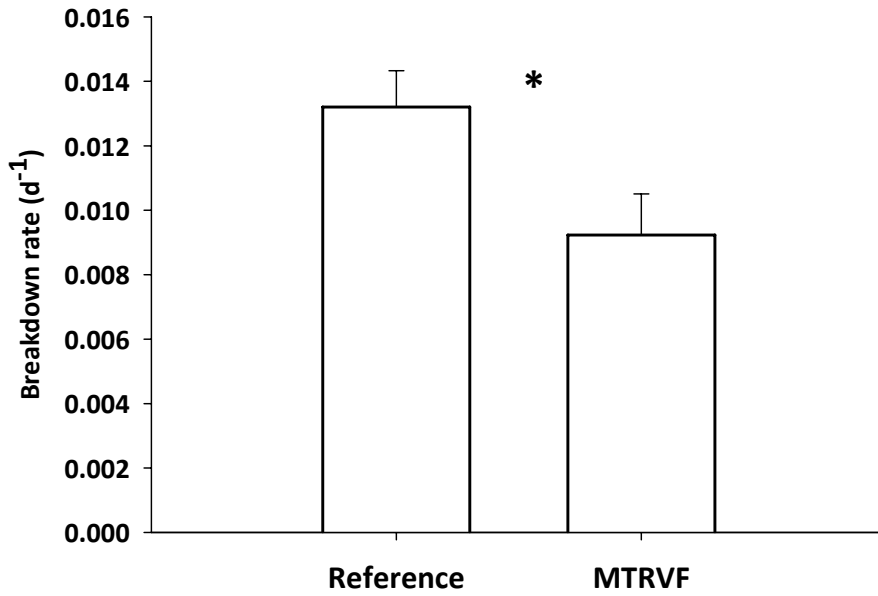
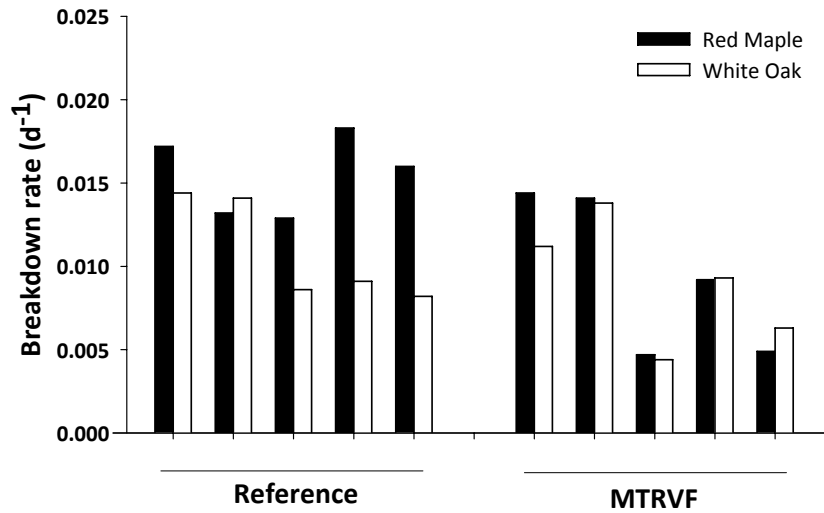


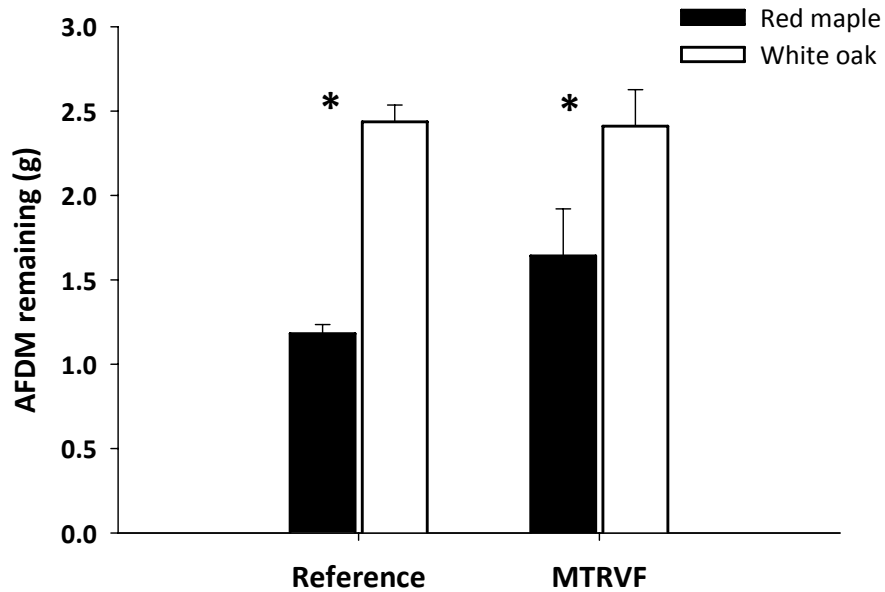
Figure 4. Breakdown rates by stream by leaf species



When the observational unit was changed from stream to leaf pack, mined stream leaf packs (Figure 5) had more leaf mass remaining at pick up dates than did leaf packs from reference streams (ANOVA, $p < 0.0001$). Red maple leaf packs contained less leaf material than white oak leaf packs (ANOVA, $p < 0.0001$) for both MTRVF and reference

streams. Likewise, there was an interaction between stream type and leaf species (ANOVA, $p < 0.0001$) affecting the amount of leaf mass remaining in collected leaf packs.

Figure 5. Mean (± 1 SE) mass of organic matter remaining in leaf packs at pick up dates.



Shredding macroinvertebrates:

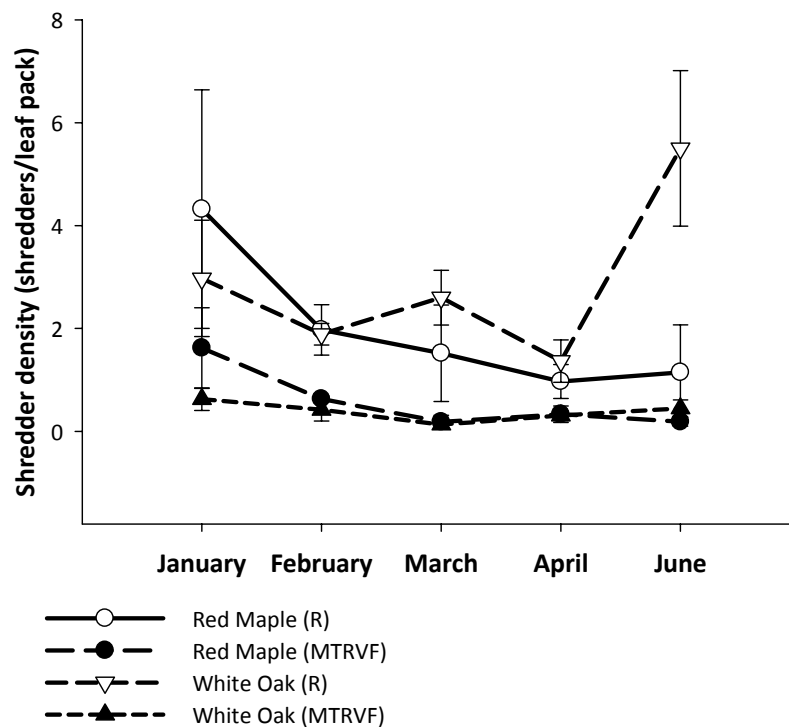
Shredder density per leaf pack was higher in reference streams ($p < 0.0001$) than mined streams (Figure 6). Shredder numbers in reference streams varied from zero to 39 organisms per leaf pack, while the highest number of shredders counted in MTRVF leaf packs was 11. Diversity was over twice as high in reference streams compared to MTRVF streams; there were 9 genera of shredders in reference leaf packs compared to 4 in MTRVF leaf packs (Table 2). Leaf species had no effect on shredder density in either MTRVF or reference streams (ANOVA, $p = 0.28$), but shredder density varied with time (ANOVA, $p = 0.0006$). Shredder density was highest in red maple leaf packs in January

in reference streams, but did not peak in reference white oak leaf packs until June, when shredder density in red maple leaf packs had declined.

Table 2. Shredder genera found in study streams.

Reference	MTRVF
Diptera	Diptera
<i>Tipula</i>	<i>Tipula</i>
Plecoptera	Plecoptera
<i>Allocaenia</i>	<i>Capnia</i>
<i>Leuctra</i>	<i>Leuctra</i>
<i>Ostrocerca</i>	<i>Ostrocerca</i>
<i>Peltoperla</i>	
<i>Tallaperla</i>	
Trichoptera	
<i>Glossosoma</i>	
<i>Lepidostoma</i>	
<i>Pycnopsyche</i>	

Figure 6. Mean (± 1 SE) shredder density in leaf packs by month.



Sediment accumulation in leaf packs:

Fine sediment accumulation on leaf packs ranged from 0.16 g in a reference stream to a maximum of 27.2 g in a MTRVF stream. Coarse sediment levels ranged from 0.18g in a reference stream to 29.6 g in a MTRVF stream. Mean accumulations of fine and coarse sediment per leaf pack were higher in MTRVF streams than reference streams (Figure 7; ANOVA, fine $p < 0.0001$; ANOVA, coarse, $p = 0.04$). There was no difference in sediment accumulation on leaf packs by leaf species type (ANOVA, fine $p = 0.48$; ANOVA, coarse, $p = 0.47$). Fine sediment accumulation (Figure 8) was closely related to the percentage of stream channel that was filled ($r^2 = 0.74$, $p < 0.001$), while coarse sediment accumulation did not appear to be related to the degree of fill in stream channels ($r^2 = 0.29$, $p = 0.06$).

Figure 7. Mean (± 1 SE) sediment accumulation on leaf packs by stream type

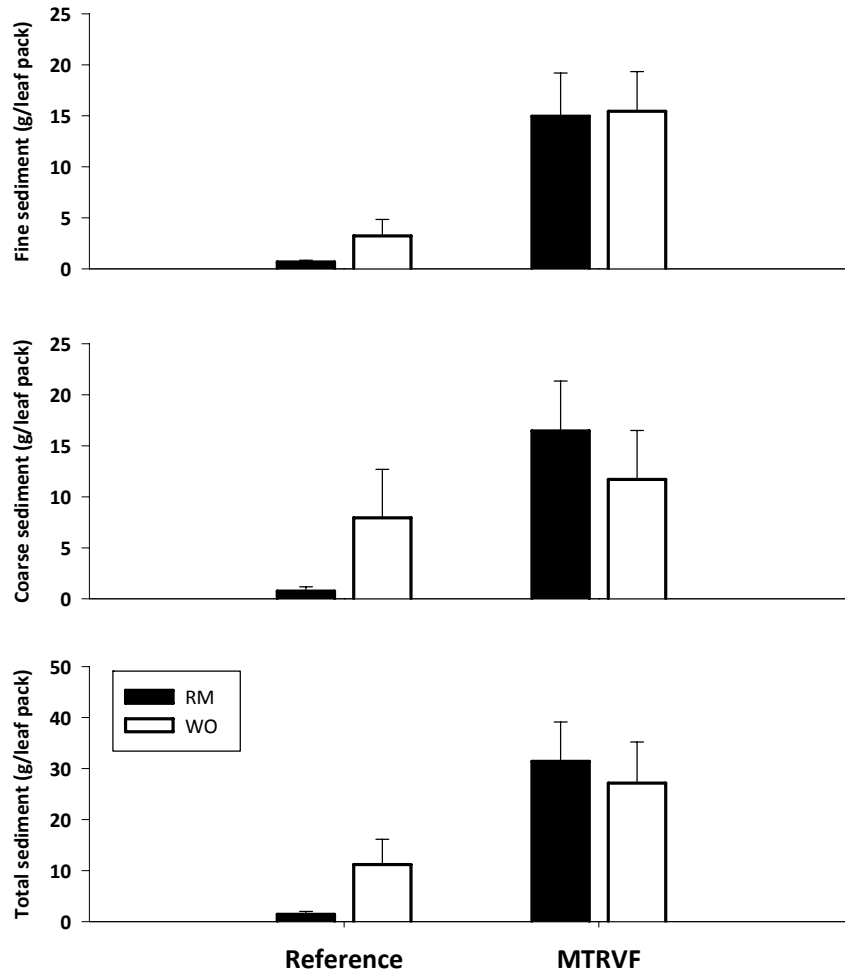
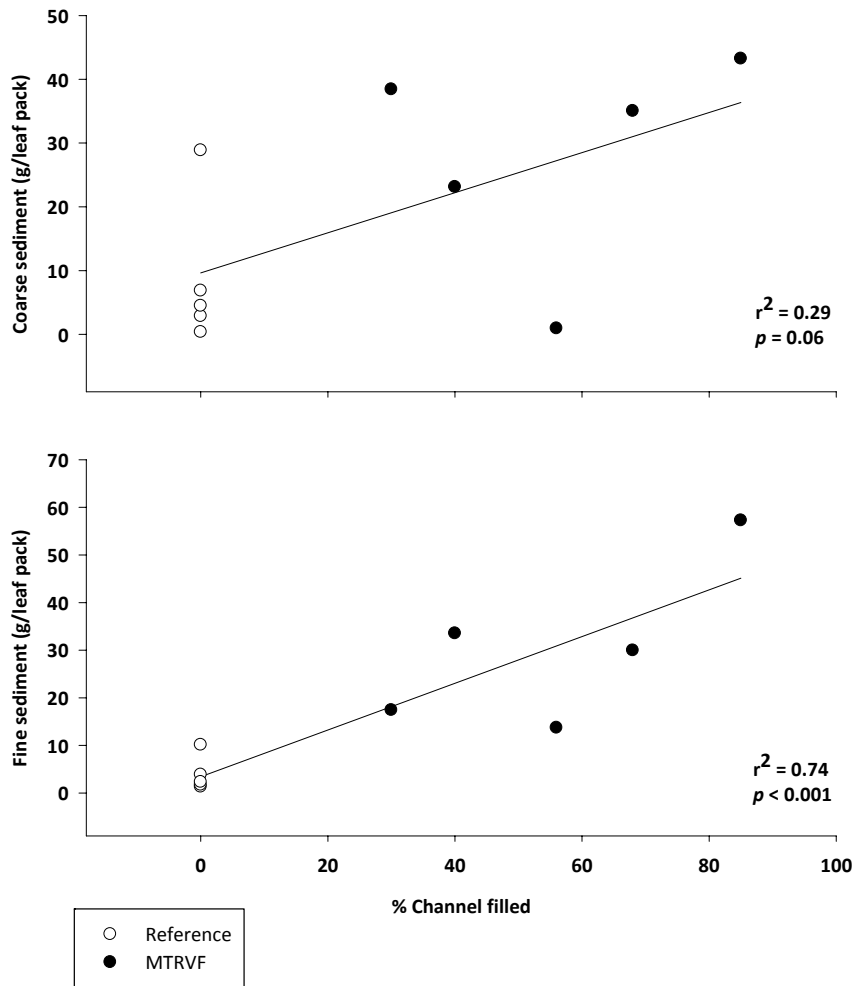


Figure 8. Sediment accumulation by percentage of channel filled

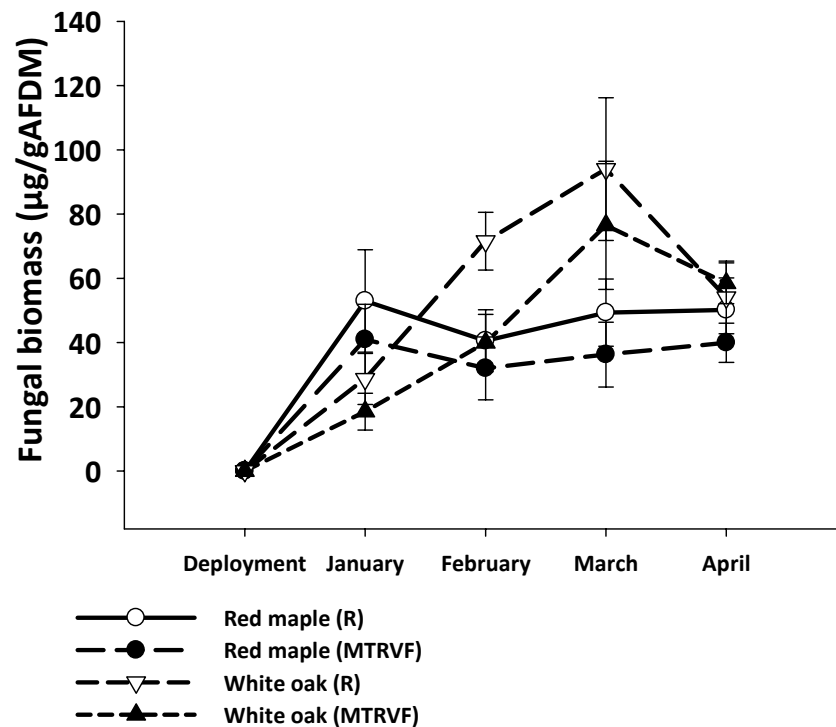


Fungal biomass:

Fungal biomass accumulation on red maple leaves was greatest in reference streams in January, where it ranged from 18.6-102.8 $\mu\text{g/gAFDM}$. Fungal biomass on red maple leaves was also highest during January for MTRVF streams, where it ranged from 26.4-84.4 $\mu\text{g/gAFDM}$. Fungal biomass on white oak leaves was highest in March in both reference (115.2 $\mu\text{g/gAFDM}$) and MTRVF (136.4 $\mu\text{g/gAFDM}$) streams. There was high variation in fungal biomass in both stream type and on both leaf type (Figure 9), and therefore fungal biomass accumulations were not different from one another either in

MTRVF or reference streams ($p = 0.11$). Likewise, leaf species type did not appear to affect fungal biomass, because there was no appreciable difference between the fungal biomass of red maple and white oak leaves ($p = 0.11$). Fungal biomass on leaves did change over time ($p = 0.005$), generally increasing quickly on red maple leaves and then slowly decreasing. Fungal biomass on white oak leaves increased slowly and then began to decrease by April.

Figure 9. Mean monthly fungal biomass

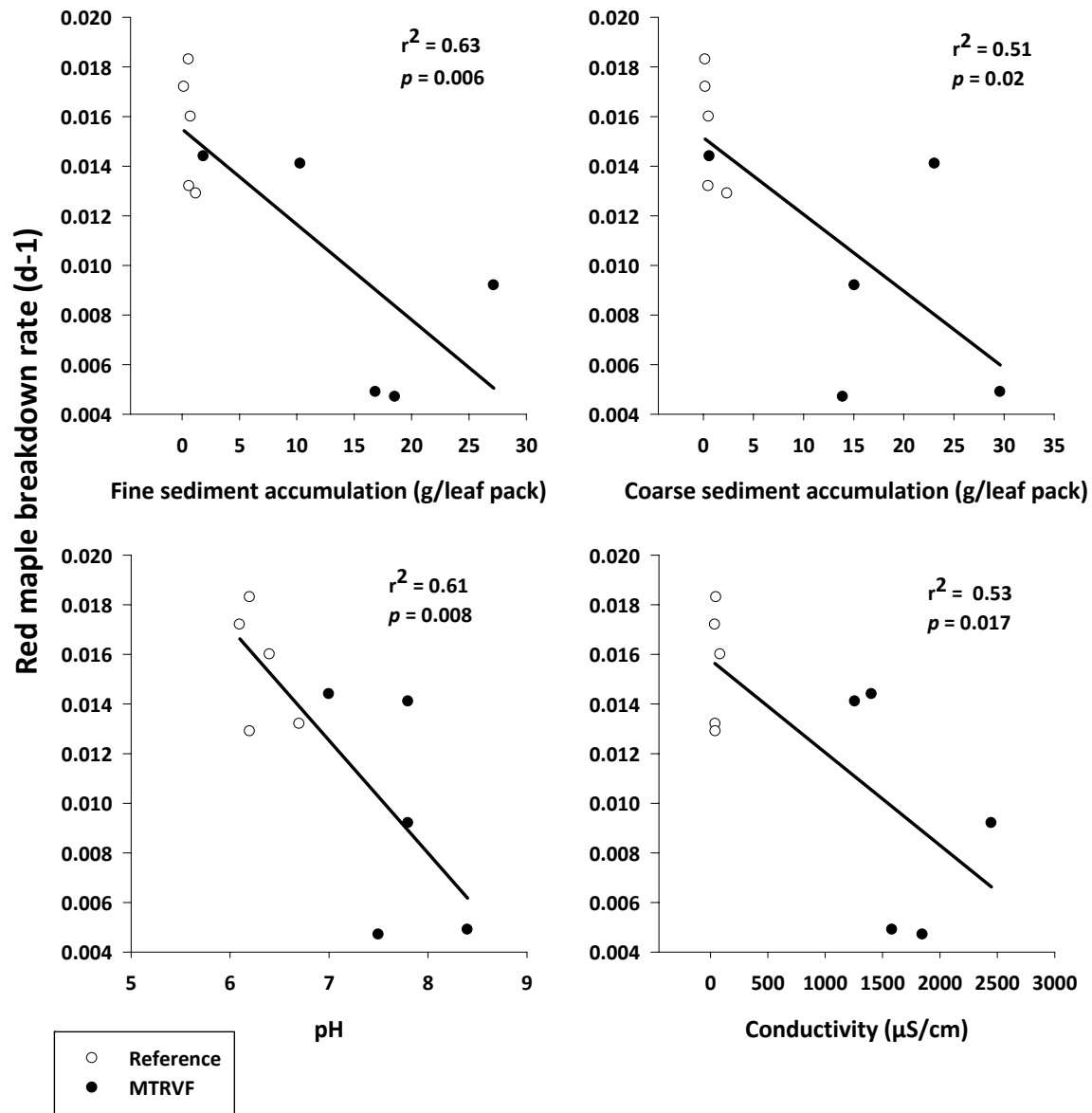


Factors influencing breakdown rates:

Red maple breakdown rates were significantly related to fine and coarse sediment accumulation in both reference and MTRVF streams (Figure 10). Red maple breakdown rates were also related to background conductivity and pH. Conversely, red maple breakdown rates were not related to either shredder density or fungal biomass. Red

maple breakdown rates were not related to other physical or chemical variables in either type of stream.

Figure 10. Factors influencing red maple breakdown rates across types of streams



White oak breakdown rates were not affected by physical or chemical variables in either stream type. Conversely, white oak breakdown rates were related to mean fungal biomass in both reference and MTRVF streams (Figure 11), but they were not linked to shredder density for either stream type (Figure 12).

Figure 11. White oak breakdown rates and average fungal biomass

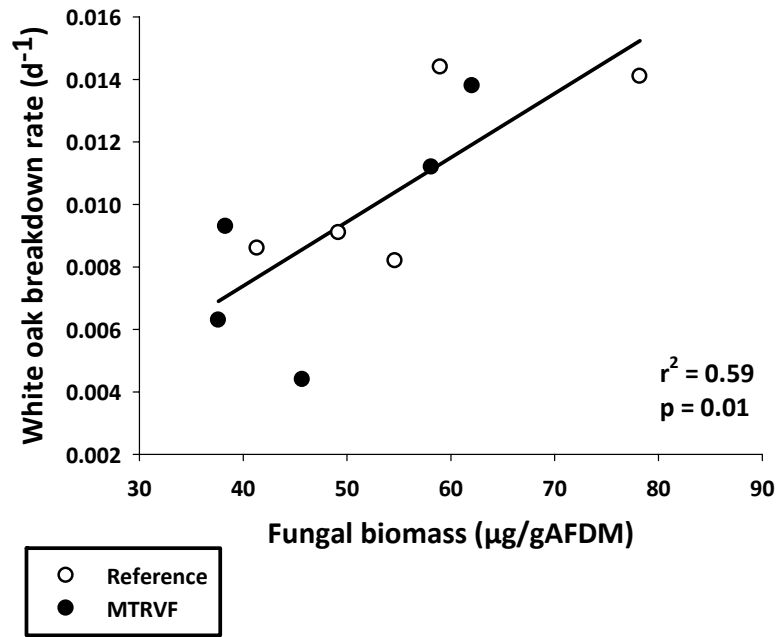
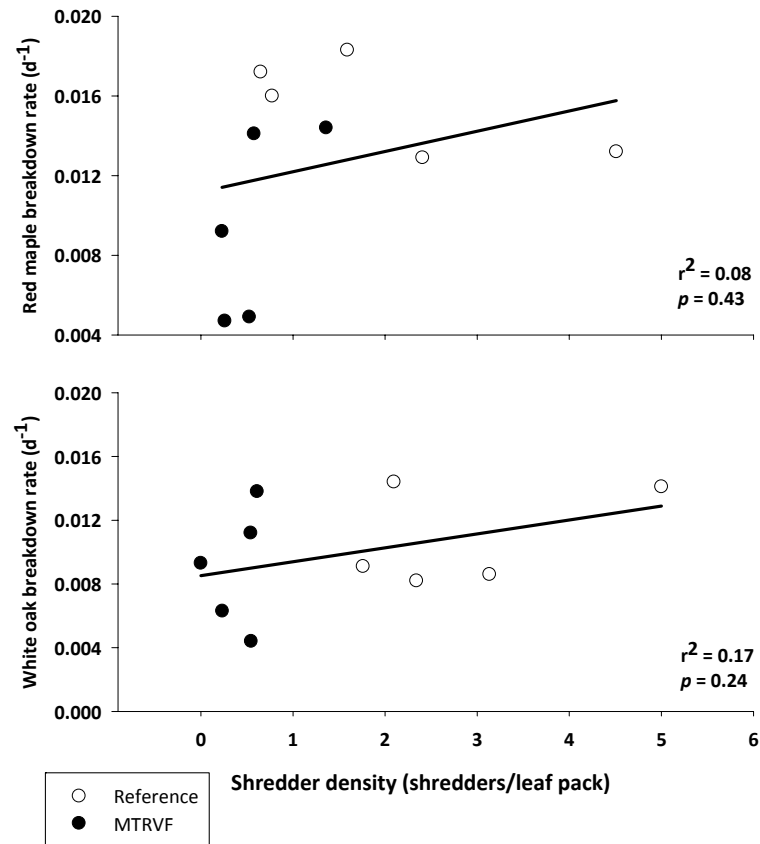


Figure 12. Leaf breakdown rates and shredder density



Discussion:

Leaf breakdown:

Reference streams demonstrated established patterns of leaf breakdown. Red maple leaves broke down more quickly than white oak leaves, a trend firmly established in the literature (Webster and Benfield 1986). The relationship of conductivity, pH, and sediment accumulations to breakdown rates suggest that red maple processing in both reference and MTRVF streams is controlled through physical processes.

Conversely, white oak breakdown rates in reference streams were unrelated to physical variables, like sediment or pH. White oak is a more refractory leaf than red

maple, and the alteration of physical conditions in MTRVF streams, e.g. increased base flow and sediment accumulation, may have had less of an effect on the physically controlled aspects of breakdown on the tougher white oak leaves than the more fragile red maple leaves.

Leaf breakdown rates in MTRVF streams were slower than those of reference streams. Both red maple and white oak leaf breakdown rates were slower in MTRVF streams, although red maple rates were slowest in MTRVF streams.

Shredding macroinvertebrates:

Shredder density and diversity per leaf pack were greatly reduced in MTRVF streams. During some months no shredders were present in leaf packs, particularly in Lost Creek, Sugarcamp Branch, and Hardaway Branch. Shredders are a key factor in leaf breakdown, responsible for approximately 60% of leaf breakdown occurring in forested streams (Hieber and Gessner 2002). Loss of macroinvertebrates has been associated with significant reduction of organic matter processing in headwater streams (Cuffney et al. 1990), and the slowed breakdown rates in MTRVF streams may be, in part, a consequence of shredder absence.

Taxonomic diversity may directly control leaf breakdown rates (Huryn et al. 2002), possibly through mechanisms like facilitation among shredders (Jonsson and Malmquist 2003). Shredder diversity was more limited in MTRVF streams, where 4 genera of shredders were found, compared to reference streams, where 9 genera of shredders were present in. When shredders were present in MTRVF streams, they belonged to genera known for being pollution tolerant organisms, such as *Tipula* (Merritt

and Cummins 2006). Sensitive shredder genera, like *Tallaperla* and *Lepidostoma*, were not found in MTRVF streams, although they were abundant in reference streams.

The elevated conductivity of MTRVF streams may have directly influenced macroinvertebrates. While short term elevation in stream conductivity is generally not harmful to aquatic macroinvertebrates (Blasius and Merritt 2002), long-term exposure to elevated conductivity may interfere with their osmotic regulation (Pond et al. 2008). Settlement ponds are designed by mining companies to address water quality problems, but conductivity remains high in MTRVF streams. Hartman et al. (2005) and Pond et al. (2008) both found depauperate macroinvertebrate communities below settlement ponds and suggested that elevated conductivity might be responsible for altered assemblages downstream of valley fills.

Macroinvertebrate density was unrelated to either leaf breakdown rates or the mass of organic matter remaining in leaf packs in both reference and MTRVF streams and therefore altered macroinvertebrate assemblages in MTRVF streams appeared to have little effect on leaf breakdown rates. This lack of an expected relationship might be a consequence of the way macroinvertebrate presence was assessed. Measures like shredder biomass might have yielded more insight into the relative importance of shredders in leaf breakdown in these streams although some studies suggest that in disturbed systems density provides as much information as biomass (Huryn et al. 2002). A more likely explanation for the reason shredders density was not related to breakdown rates in either type of stream is that there simply were not many shredders in these streams. Shredder density in all types of streams was low compared to published densities for the central Appalachian streams (Harding et al. 1998; Stone and Wallace

1998). Low density of shredders would certainly reduce the role of shredders in the leaf breakdown process, especially because many of the obligate shredders found in leaf packs were very small, such as *Capnia*, and would have little influence on leaf breakdown.

Low shredder density in MTRVF streams may be a product of high conductivity, but low macroinvertebrate density in reference streams are probably a consequence of low flow during the summer. All reference streams had very low flow or were completely dry during October 2007 and water levels had begun to drop during July 2008 sampling periods. Summer drying would impose a strong selective pressure on macroinvertebrates to those capable of withstanding such harsh conditions and thereby greatly reduce the potential diversity and density of macroinvertebrates present in these systems (Lytle and Poff 2004).

Sediment accumulation:

High sediment levels in streams are often associated with surface mining disturbance (Wood and Armitage 1997), because mining exposes soils to erosion or destabilizes stream channel banks. Bonta (2000) found elevated sediment loads in streams draining surface-mined watersheds, even twenty years after mining and reclamation activities had ended. Accumulation of fine and coarse sediment on leaf packs was much higher in MTRVF streams, and it is likely that the high sediment levels on leaf packs in MTRVF streams are responsible for slow breakdown rates. The highest fine sediment accumulations were found in watersheds with highest percentage of filled stream channel length and, incidentally, within streams which had the lowest leaf breakdown rates. High sediment loads in MTRVF streams buried leaf packs and may

have eliminated physical aspects of the leaf breakdown sequence. Because MTRVF channels in this study were unstable and migrated over their floodplains, some channels were abandoned and stranded leaf packs in stream banks. This burial would effectively halt breakdown by insulating leaf packs from physical abrasion (Herbst 1980) and limit shredder access to leaf material. Deliberate burial of leaf packs, using leaf species with fast and slow breakdown rates, has shown that burial decreased the breakdown rates of the fast species (e.g. maple) more than the slow species (e.g. oak) (Herbst 1980).

Increased sediments in streams also have an adverse affect on macroinvertebrates (Wood and Armitage 1997; Viera et al. 2004; Matthaei et al. 2006). An increase in fine sediments, both as bed and suspended load, can interfere with macroinvertebrate respiration when sediment accumulates on their gills (Lemly 1982). Stream embeddedness can also decrease channel heterogeneity, resulting in diminished habitat and refugia from disturbance for macroinvertebrates (Wood and Armitage 1997; Schofield et al. 2004). Consequently, the loss of suitable habitat in headwater reaches may have eliminated most macroinvertebrates and ended the influx of macroinvertebrates to lower reaches through drift.

Fungal biomass:

High dissolved metal concentrations and acid mine drainage have been previously associated with ecosystem function impairment in streams influenced by mining. Gray and Ward (1983) found that breakdown rates were reduced in streams affected by mining drainage, regardless of water quality amendment, because microbial communities were prevented from colonizing leaves by interference of metal flocculates, and leaves were therefore less palatable to shredding macroinvertebrates. Maltby and Booth (1991) and

Niyogi et al. (2001) noted similar alterations to fungal communities and subsequent decreased macroinvertebrate consumption of leaves; however, we found no acid mine drainage in these streams. pH was elevated in MTRVF streams, regardless of the presence of settlement ponds, and, consequently fungal biomass does not appear to be limited by acidic conditions in MTRVF. Because fungal biomass was not different between types of streams, it seems unlikely that the microbial colonization to shredder step on the leaf processing continuum (Petersen and Cummins 1974) is disrupted by MTRVF. Rather, white oak breakdown rates were related to fungal biomass, suggesting that fungal activity actually played an important role in the breakdown of leaves in both MTRVF and reference streams.

River network connectivity:

Differences between MTRVF and reference stream structure and function might further be explained by severity of disturbance. Reference streams were not pristine, because the catchments they drain are undergoing secondary succession after logging and road construction. MTRVF stream catchments are undergoing primary succession (Simmons et al. 2008). The complete removal of vegetation and developed soil, resulting in exposed bedrock, and an unstable channel in MTRVF sites bears similarities to conditions associated with landscapes developing after glacial retreat in Glacier Bay, Alaska (Milner et al. 2007). Stream structure and function have taken tens of years to develop in post-glacier conditions and have yet to achieve the levels measured in nearby, non-glaciated stream (Milner et al. 2007).

The loss of multiple levels of control of ecosystem function observed in MTRVF streams, from species to organism to physical, is a direct consequence of the

disorganization of the system. Huttel and Weber (2005) note that, while ecologically destructive, surface mining provides an opportunity to study the development of ecosystems from a known starting point. The fills in the catchments of the streams examined in this study are no more than 20 years old, which would suggest that upstream riparian zones are too young to have established ecosystem function, and, consequently would be unable to mediate downstream processes through organic matter transports, control of the hydrologic regime, and macroinvertebrate drift.

Loss of established headwaters by valley fills produces both temporal and spatial disconnections within river systems. The downstream portions of this study system display a lack of pattern in ecosystem function, in spite of established riparian zones, which should help buffer streams from the influence of disturbance (Freeman et al. 2007). Studies of landscape development (Bonta 2000) and succession in other surface mined sites (Huttel and Weber 2005; Simmons et al. 2008) indicate that reestablishment of ecosystem processes take tens of years. Consequently, the alteration of energy pathways like leaf breakdown in river networks by MTRVF may take centuries to return to pre-disturbance levels.

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