Selected Carbon Dynamics as Functional Indicators of Restoration Success in Headwater Streams Impacted by Coal Mining: Progress from the First Two Years

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Executive Summary

Continued permitting of coal mining in the central Appalachians is dependent on maintaining or restoring ecosystem structure and function in streams affected by coal mining. The Clean Water Act [CWA, section 404] compensatory mitigation rule requires mitigation of stream impacts attributable to valley fill and other mining activities (Federal Register April 10, 2008). Although assessments of stream reconstruction efforts are generally rare, stream ecosystem assessment is required to determine the success of post-mining mitigation efforts. Until recently, reliance on measures of biotic, physical, and chemical components of the stream ecosystem has been the norm for these stream assessments. Common measures of this type include concentrations of chemical components, distribution and abundance metrics of organisms occurring in the stream channel, and sediment particle-size distributions. Measures of this type are generally taken at discrete points in time (e.g., monthly, seasonally, or biennially) and have been referred to as *structural measures*. Historically, structural measures have been used to infer performance or *function* of systems through time. Criticisms of using structural measures as surrogates for functional measures have become common in scientific and regulatory literature within the past few years primarily because the USEPA (2010), under the CWA, requires *direct* measurements of ecosystem function as well as structure. Furthermore, relationships between structural and functional measures remain untested and potentially tenuous for many disturbances (Wallace and Webster 1996; Bunn and Davies 2000).

In conjunction with structural measures, functions that integrate various ecosystem components should be measured to obtain a thorough assessment of stream ecosystems subjected to restoration efforts at minimal cost. Carbon (C) as organic matter is an important structural measure because it provides habitat and fuels ecosystems. The manner in which organic matter is imported, generated, stored, and exported (i.e. functions) is regulated by physical, chemical, and biotic ecosystem components and can be used to describe energy flow within a stream ecosystem with implications for the downstream environment.

This study aims to measure selected C functions in eight low-order reconstructed streams affected by mining and in four relatively undisturbed forested reference streams. Three C functions that are relatively straightforward to implement and relate directly to various ecosystem components have been identified to assess the sources and processing of C in these streams. Based on the selected measures of C dynamics, this research will:

1. assess the condition of coalfield streams receiving restoration practices relative to forested reference streams,
2. examine relationships between functional and structural assessments of reconstructed streams and reference streams,
3. determine factors affecting these processes in streams receiving restoration practices,
4. evaluate these measures as indicators of stream condition.

Background and Justification:

Important Carbon Functions: Though studies of C budgets provide a holistic view of ecosystem energy flow via measurement of storage, inputs, and outputs, these studies require high-intensity sampling efforts and are costly, thus limiting their utility within management and assessment frameworks. With regard to assessment of C dynamics, measures of organic matter transport, production, and detrital processing within stream corridors provide manageable alternatives to assessment of comprehensive C budgets. These parameters provide insight into the energetic function of stream ecosystems, while restricting sampling requirements to manageable levels. In conjunction with structural assessment and routine physiochemical monitoring, assessment of C dynamics within restored streams not only provides a sound basis for determining levels of energetic function, but also allows for insight into factors that control these processes.

In terms of energy flow, many studies have shown forested headwater streams to be predominantly open ecosystems, governed by allochthonous inputs (meaning materials produced outside the stream channel) of organic matter (e.g., Fisher and Likens 1973; Cummins 1974; Vannote et al. 1980; Hall et al. 2000). Thus, quantification of organic matter input rates to the stream channel from the riparian zone partially describes energy inputs. It has also been determined that autochthonous inputs (organic matter generated within the stream channel) from primary producers can contribute significantly to ecosystem dynamics in many minimally canopied (especially desert) streams (e.g., Minshall 1978; Busch and Fisher 1981). Because canopy cover varies among streams selected for study, and many of the reconstructed streams are sparsely canopied, it stands to reason that periphytic biomass accrual rate could be an important contributor to C inputs in some of these streams. Lastly, comparing rates of leaf litter breakdown between reconstructed versus reference streams provides an index of functional ecosystem condition, which integrates and can be related to physical, chemical, and biotic factors. The C functions being assessed in this study are discussed in greater depth below:

- *Riparian organic matter subsidies.* The quality and quantity of organic matter input to and transported through the stream corridor greatly influences biotic assemblage structure which, in turn, influences the quality and quantity of organic matter available to downstream environments. Riparian inputs of coarse particulate organic matter (CPOM) as leaves or twigs and branches, for instance, may undergo leaching or fractionation to produce dissolved organic matter (DOM) or fine particulate organic matter (FPOM), respectively. The magnitude and rate of these processes depends on spatiotemporally heterogeneous factors, such as season and stream type, as well as the quality and quantity of CPOM entering the stream across ecosystem boundaries. As such, characterization of terrestrial subsidies to the aquatic system as leaves and other forms of litter is an essential component to determining the availability of resources to the biotic assemblage with clear implications for downstream environments. Ideally, comprehensive understanding of CPOM inputs would include contributions from upstream of research sites as well as the riparian zone. However, in-stream sample nets require frequent retrieval to keep from filling and may interfere with concurrent experiments. In contrast direct-fall inputs of litter can be readily characterized over relatively long periods, while still providing information about resources available to *in situ* and downstream assemblages.

- *Leaf litter processing.* Gessner and Chauvet (2002) have presented a compelling case for use of leaf litter breakdown in functional assessments of stream ecosystems. Moreover, multiple studies have identified leaf litter and organic matter processing as ecosystem functions essential to maintenance of *in situ* and downstream environments (Wallace et al. 1982a; Wallace et al. 1982b; Fisher and Gray 1983; Hutchens and Wallace 2002; Simmons et al. 2008; Aldridge et al. 2009; Benstead et al. 2009). Leaf litter breakdown is a function of both biotic processes, such as microbial and macroinvertebrate activity, and abiotic processes, such as chemical breakdown and leaching of organic compounds. Because biotic activity may be indexed by leaf-litter breakdown rates (Simmons et al. 2008), breakdown coefficients may be regarded as bioindicators of functional condition. Leaf litter breakdown rates integrate changes in environmental quality over time. Comparison of leaf litter breakdown rates of reaches that have received reconstruction practices to those of reference and/or pre-restoration conditions allows for quantitative and objective assessment of ecosystem function and subsequently can serve as an indicator of ecological restoration success (Table 1).

Table 1. Framework for assessing stream functional integrity from leaf litter breakdown (from Gessner and Chauvet 2002).

Method	Assessment parameter	Criterion	Score
Comparison with reference	Ratio of breakdown coefficients at impacted (k_i) and reference (k_r) site	$k_i:k_r$ = 0.75–1.33	2
		$k_i:k_r$ = 0.5–0.75 or 1.33–2.0	1
		$k_i:k_r$ < 0.5 or >2.0	0
Absolute value	Breakdown coefficient at impacted site (k_i)	k_i = 0.01–0.03/d	2
		k_i = 0.005–0.01/d or 0.03–0.05/d	1
		k_i < 0.005/d or >0.05/d	0
Absolute value of ratio	Ratio of breakdown coefficients in coarse (k_c) and fine (k_f) mesh bags†	$k_c:k_f$ = 1.2–1.5	2
		$k_c:k_f$ = 1.5–2.0 or <1.2	1
		$k_c:k_f$ > 2.0	0

† If sizable numbers of shredders are predicted to occur in the stream.

- <u>*Primary Production.*</u> *In situ* rates of primary production within a stream may be determined by changes in dissolved O_2 or CO_2 concentration, pH, ^{14}C incorporation, or indexed by the change in standing crop over time, given control for losses caused by grazing, scour, and migration (Steinman et al. 2006). Although each method has advantages and limitations, efficient assessment is predicated upon constraints of time and funding. Chlorophyll *a* (chl *a*) is the predominant photopigment common to all primary producers, and concentrations thereof have been used as surrogates for algal standing crop. Measurement of chl *a* is not a demographic measure of population or community (i.e., biotic structure), and as such, calculated differences in this photopigment over time can be used to estimate accrual rates of algal assemblages. Accrual rates incorporate gains in the number and size of individuals, as well as any losses due to herbivory, scour, or sloughing. Conceptually, accrual rates of benthic algae and net primary production (NPP) should be roughly equivalent when controlled for losses due to physical and biotic processes.

<u>Progress to date:</u>

From September 2009 through June 2010, we designed a study that measures important stream ecosystem functions and structure, and scouted more than 100 streams to be included in the study using preliminary measurements to identify study sites from the candidate pool of streams. Sites with comparable slope were delineated above ephemeral confluences and basic site surveys were taken in July 2010 according to methods outlined in Fritz et al. (2006). Additionally, regular meterable measurements were initiated during this month. From July 2010 through early December 2010 substrates (i.e., periphytic biomass accrual tiles and leaf litter breakdown bags) and collection devices (i.e., litterfall traps) to determine the functions for study were prepared and deployed along with temperature data loggers (HOBO U22-001 Water Temp Pro v2; Onset Computer Corp.). Retrieval of samples and substrates has continued at approximately monthly intervals and processing of collected samples is ongoing.

Preliminary assessment of ecosystem function (i.e., stream metabolism) for six restored/reconstructed streams and three non-restored/reconstructed streams had been conducted by previous members of the research team (Northington et al. 2009), and some of these original study streams were retained for this study. Additional streams were identified to augment the population of streams used in the previous study through our scouting efforts. Reconstructed/restored streams affected by active deep mine discharge, as well as those deemed incomparable based on physical characteristics and additional stressor sources to aquatic biota were excluded from the study. Minimally impacted reference streams were identified as those that lack evidence of recent significant watershed disturbance by humans, and with specific conductance $\leq$ 150 $\mu S\ cm^{-1}$ and circumneutral pH (6-8). Eight reconstructed streams and four reference streams were ultimately selected for study (Table 2).

Table 2. Location and general description of streams selected for study.

Stream Name	Location	Stream Type[1]	Stream Order[2]
Sewing Creek	Buchanan County, VA	MRR	1
Shooting Range Creek	Buchanan County, VA	MRR	1
Chaney Creek	Russel County, VA	MRR	2
Laurel Branch	Russel County, VA	MRR	1
Stonecoal Creek	Russel County, VA	MRR	1
Callahan Creek	Wise County, VA	MRR	1
Critical Fork	Wise County, VA	MRR	2
Guest Mountain #3	Wise County, VA	MRR	2
Copperhead Branch	Buchanan County, VA	UFR	1
Big Branch	Dickenson County, VA	UFR	1
Crooked Branch	Dickenson County, VA	UFR	2
Middle Camp Branch	Dickenson County, VA	UFR	1

[1] Two stream type categories have been identified, mined receiving reconstruction practices (MRR) and un-mined forested reference (UFR).

[2] Stream order was determined using 7.5' USGS quadrangles.

The majority of eight reconstructed streams selected have received reconstruction efforts within the past 6-7 years, though a few are older. Primarily because of variation in reconstruction techniques, these stream corridors are characterized by riparian zones in multiple stages of development. Relatively few restoration efforts located are >6 years old, however, and those with developing forest in the watershed generally lack mature riparian canopy. In an effort to expand the study, additional contacts were made to assist in locating mining-impacted streams where restoration or reconstruction efforts have resulted in establishment of more developed riparian canopy. Additionally, “comparably canopied” reference streams, which are relatively unimpacted by other disturbance were sought to discern between scale-dependent (e.g., local riparian vs. watershed forest) controls on selected C dynamics. No such streams were discovered after several scouting trips and contacts, and as such, we are confident that streams of this nature are rare in the region, if they exist.

Based on sampling from the first year of data collection (the 2nd year of the study following stream scouting and identification) and observation, several differences among streams of the same type (within UFR and MRR classifications) as well as between reference and reconstructed streams were apparent (Table 3). Reconstructed streams selected for study exhibit a wide range of mean specific conductance values (Table 3, Figure 1). Although the range of mean specific conductance values for reference streams is more densely clustered, a range from 49.8 μS cm-1 to 134 μS cm-1 (Table 3, Figure 1), these data lend themselves to regression analyses to determine relationships between specific conductance and other structural and functional measures described above. Moreover, samples from these streams show a gradient of variation in other variables (e.g., SO42-, percent canopy cover), which allows for analysis of factors that may influence litter breakdown, periphytic biomass accrual, and benthic macroinvertebrate community structure.

Table 3. Selected physical and chemical variable means for mined streams receiving reconstruction practices (MRR) and un-mined forested reference streams (UFR).

Stream Name	Specific Conductance ($\mu S\ cm^{-1}$)	Temperature (°C)	pH	SO_4^{2-} ($mg\ l^{-1}$)	Cl^- ($mg\ l^{-1}$)	NO_2+NO_3-N ($mg\ l^{-1}$)	NH4-N ($mg\ l^{-1}$)	% Canopy Cover	D_{50} (mm)
MRR									
Callahan Creek	779	13.12	8.40	211.06	4.66	1.59	0.02	27	32.0
Critical Fork	1513	13.60	8.04	693.80	0.98	5.73	0.04	9	22.6
Guest Mountain #3	666	13.45	7.89	237.76	0.72	0.54	0.01	22	128.0
Laurel Branch	669	12.84	7.82	163.80	2.35	1.76	0.01	20	16.0
Chaney Creek	451	13.05	7.66	137.58	1.29	2.32	0.02	75	16.0
Sewing Creek	1386	14.03	7.81	691.70	25.82	3.75	0.02	25	2.0
Shooting Creek	1712	11.70	7.95	770.48	3.97	8.08	0.01	24	32.0
Stonecoal Creek	172	12.83	7.47	35.33	1.03	0.90	0.02	8	5.6
Mean + SE[1]	918.4 ± 194.7	13.08 ± 0.2	7.88 ± 0.1	367.7 ± 5.1	5.1 ± 3.0	3.1 ± 0.9	0.02 ± 0.004	26.2 ± 7.4	31.8 ± 14.3
UFR									
Big Branch	80.3	12.00	7.45	12.18	5.36	0.55	0.02	86	16.0
Copperhead Branch	134	11.37	7.42	19.61	2.44	0.70	0.01	85	11.0
Crooked Branch	70.9	12.10	7.47	9.22	5.81	1.03	0.01	79	8.0
Middle Camp Branch	49.8	12.13	7.35	9.90	0.68	2.06	0.02	78	32.0
Mean ± SE	83.7 ± 17.9	11.90 ± 0.2	7.42 ± 0.03	12.7 ± 2.4	3.6 ± 1.2	1.1 ± 0.3	0.02 ± 0.002	82.0 ± 2.1	16.8 ± 5.3

[1] Grand means with standard errors are expressed below each stream group (MRR and UFR).

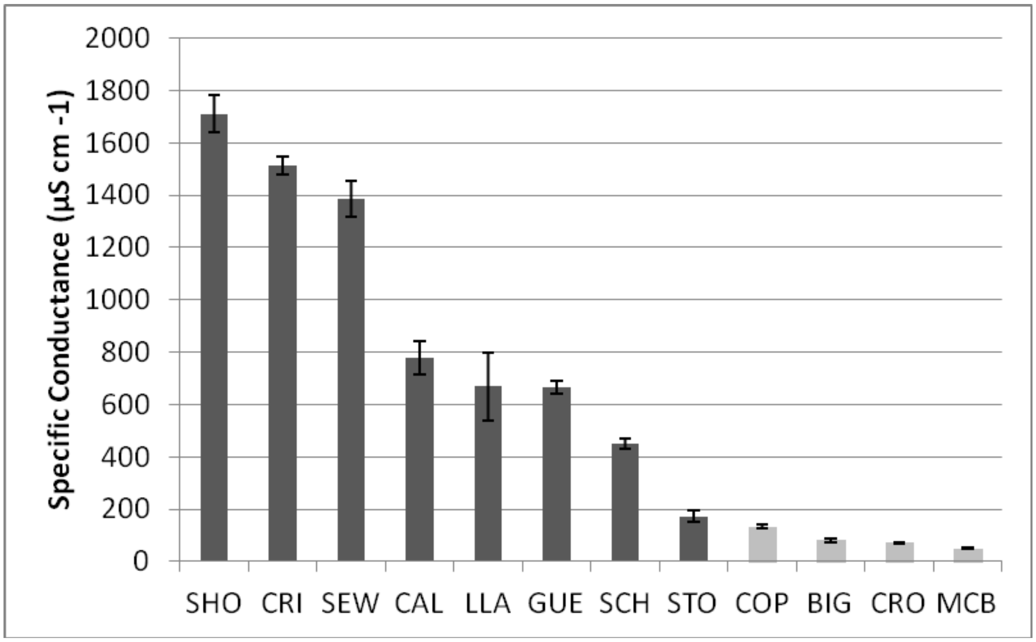

Figure 1. Mean specific conductance for MRR (dark gray) and UFR (light gray) streams.

Projections

Third Year: Processing of the first year of sample and substrate collection (2nd year of study) will continue through the third year. Artificial substrates to determine periphytic biomass accrual and leaf litter breakdown bags will be deployed and collected along with physicochemical samples for another year. Statistical analysis of data from the second year of the study (first sample year) will continue with projected completion by the end of the third year of funding. Geospatial data are being obtained to determine local watershed factors that may influence the C functions measured. Regression analysis will be used to relate functional data to structural factors (or other functional variables such as litterfall input). Other analyses (e.g., multivariate data analysis) may be used where appropriate. A preliminary set of continuous and categorical explanatory and response variables have been assembled (Table 4).

Fourth Year: Samples, litter breakdown bags, and artificial periphyton substrates will be collected through fall of the fourth year of the study. Sample processing will continue through early spring of the fourth year of the study, and results will be analyzed in a manner similar to the previous year. Results will be synthesized and a report of two years of data collection will be available by the summer of the fourth year of the study (2013).

Expected Outcomes

Based on observations from the first year of data collection, variation in several structural stream variables is apparent. Although processing of samples to determine functional measures has not been completed, cursory observations from processing suggest that there will be sufficient variation among streams to help determine factors influencing these functions through regression analysis. Moreover, this research will benefit the scientific community, regulatory agencies, monitoring authorities, and industry by: (1) increasing the body of knowledge associated with functional assessment of reconstructed stream ecosystems following mining activities, (2) investigating methods that may be applied for accurate assessment of the functional status of these streams, and (3) assessing effectiveness of stream reconstruction efforts and the relationships between structural and functional integrity within these stream ecosystems. With respect to our outlined objectives, we hope to guide future functional assessment through dissemination of results via presentations at professional meetings and publication in peer-reviewed journals, as well as through cooperation with industry, regulatory agencies, and consulting firms.

Table 4. Continuous independent and dependent variables to be used in regression and multivariate analysis, as well as *a priori* stream and catchment categories.

Independent Variables (x)	Dependent Variables (y)
Reach Scale Continuous	**Benthic Macroinvertebrate Structure**
Total alkalinity (mg L?^{1} as $CaCO_3$)	Total density (#/g litter remaining)
TDS (mg L?^{1})	Total Taxon richness
TSS (mg L?^{1})	EPT taxon density (#/g litter remaining)
SRP (mg PO_4-P L^{-1})	EPT taxon richness
DIN (mg L^{-1})	Shredder density (#/g litter remaining)
DOC (mg L^{-1})	Shredder richness
Dissolved NH_4-N (mg L^{-1})	Diversity Index Scores
Dissolved NO_2+NO_3-N (mg L^{-1})	
Dissolved Mn (mg L^{-1})	**Riparian Inputs***
Dissolved Fe (mg L^{-1})	Annual litterfall input rate (g AFDM m^{-2} y^{-1})
Dissolved Ca^{2+} (mg L^{-1})	Annual litterblow input rate (g AFDM m-2 d-1)
Dissolved Mg^{2+} (mg L^{-1})	Relative contribution by species (g leaf species / g total)
SO_4^{2-} (mg L^{-1})	
Br^- (mg L^{-1})	**Leaf Litter Breakdown**
Cl^- (mg L^{-1})	$\|k\|$ (d^{-1} and degree d^{-1}) **
Specific Conductance (?S cm^{-1})	$k_i : k_r$
Dissolved Oxygen (mg L^{-1})	$k_c : k_f$ ***
Temperature (°C)	
pH	**Biomass Accrual**
Canopy cover	Periphytic biomass accrual rate (mg AFDM cm^{-2} d^{-1} and degree d^{-1})
Sinuosity (thalweg dist/channel dist)	Algal biomass accrual rate (mg chl *a* cm^{-2} d^{-1} and degree d^{-1})
Channel slope (%)	Autotrophic index (mg AFDM cm^{-2} / mg chl *a* cm^{-2})
D_{50} (mm)	
Catchment Scale Continuous	
Age since mined (yr)	
Age since restored (yr)	
Age since restored (yr)	
Mining extent (% catchment mined)	
Forest extent (% forested)	
Reach and Catchment Scale Categorical	
UFR	
URI	
MRR	
Restoration Type (e.g., NCD vs. Other)	
Mining type (e.g., VF vs. strip vs. deep)	

*Riparian inputs will also serve as potential explanatory variables with respect to leaf litter breakdown and assemblage structure

****** Will be calculated for all sites, but will only applyGessner and Chauvet (2002) index to those which are not forested reference (UFR).

*** Only for standardized (*Q. alba*) leaf bags

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