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Meta-Analysis of Biological Monitoring Data to Determine the Limits on Biological Uplift from Stream Restoration Imposed by the Proximity of Source Populations

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Abstract

This study compiled biological monitoring data from 18 stream restoration sites in the counties of Anne Arundel, Baltimore, Frederick, Howard, and Montgomery. Additional data from the Maryland Biological Stream Survey (MBSS) and countywide biological monitoring programs, in adjacent stream networks, were evaluated as a predictor of biological condition at restoration sites. The amount of pre- and post-construction biological monitoring data varied widely among sites and increases in Benthic Index of Biotic Integrity (B-IBI) post-construction were apparent at only five sites. Therefore, we evaluated the relationship of B-IBIs, sampled one or more years post construction, with distance to good stream sites along the stream network in a mixed-effect model regression. The analysis showed a significant relationship between stream condition (B-IBI score) and the distance to good streams (BIBI >= 2.75) with p=0.02. There were also significant site effects, but neither the difference in the year the restoration and reference sites were sampled nor the drainage area to each site were significant. Removing the non-significant factors gave a parsimonious model $r^2=0.71$. Illustrating the variability of individual sites, only 4 of 12 restoration sites showed a significant proximity effect and the overall simple linear regression was not significant ($p=0.5$, $r^2=0.014$). The 4 sites with significant proximity effects were sampled 3, 5, 7, and 15 years post construction, generally longer than the sites not showing significant effects. This analysis supports, but does not demonstrate unequivocally, that the proximity to good stream sites is a limitation on stream restoration. It is likely that additional years of post-construction biological monitoring and inclusion of more restoration sites would improve our ability to quantify this proximity effect. Inclusion of more environmental variables at both restoration and reference sites, in addition to a more thorough investigation of macroinvertebrate compositional effects might also improve our understanding of potential interactions with spatial factors. The potential for proximity effects should temper expectations for biological uplift from stream restoration and inform the design of connected stream restorations.

1. Background

A fundamental goal of many stream restoration efforts is to rehabilitate habitat to lure desirable species assemblages from the regional species pool. This “build it and they will come” approach is widespread not only in the realm of stream restoration, but in the field of restoration ecology in general. This assumption of assemblage attraction to restored locations is not always met for a number of reasons. The first is that larger-scale degradation in a watershed supports a depauperate species pool. That is, biological uplift at a location buried in a landscape of degraded stream habitats is unlikely to occur as there is no opportunity for species adapted to natural environments to reach this location. The species pool of colonists simply does not exist. So, while restoration efforts can certainly improve habitat quality, a lack of proximity to similarly high-quality habitats is lacking. Secondly, stream networks are highly structured, imposing significant constraints on the dispersal potential of species from high-quality habitats. In central Maryland, streams are organized into dendritic or linear-branching networks. As such, these networks exhibit a well-documented gradient in isolation from the regional species pool. Headwaters and smaller streams are more isolated than more well-connected higher-order streams. Since the majority of–though not necessarily all–dispersal is along the stream corridor, the potential for colonization from other parts of the river network is much higher in high-order reaches than in headwaters, owing simply to those reaches being more well-connected to other stream locations. Evidence is mounting that this isolation results in a tight connection between assemblage structure and local environmental conditions. In higher-order reaches, assemblage structure not only responds to local habitat conditions, but also to random colonization/extinction patterns, such as source-sink dynamics.

Evidence for source pool constraints was first proposed explicitly by Lake et al (2007). A few studies outside the U.S. confirm this phenomenon. For example, in a study of the relative role of local water quality factors versus spatial position in a watershed, Kitto et. al. (2015) found that while local water quality (e.g., pH, temperature, dissolved metals, sediment) did explain variation in invertebrate assembly structure in sites restored in response to mining activity, spatial position alone did as well. Sundermann et. al. (2011) also concluded from an analysis of 24 German restoration projects and 1,231 nearby stream sites that, while local habitat failed to explain variation in invertebrate assemblage structure, proximity to an intact regional species pool did explain the variation. They investigated the relationship between “restored” ecological communities in streams to species pools estimated in 0–5, 5–10, and 10–15 km rings centered on the restored sites. Only sites with intact fauna at locations 0-5 km from restoration sites showed a response to restoration efforts. These findings are supported by analyses of MBSS data that demonstrate that the potential for proximity to adjacent species assemblages drives invertebrate community structure. While not focused on restoration per se, these analyses show that invertebrate assemblages respond strongly to regional colonization patterns in rivers that are highly connected in river networks (i.e., higher-order streams) than to lower-order, more-isolated headwaters (Brown and Swan 2010, Swan and Brown 2014).

2. Research Question

This study endeavors to answer the general research question:

- What is the effect of site condition on the outcomes of stream restoration?

This study endeavors to answer the specific research question:

- What is the effect of the proximity of high-quality biological assemblages on the success of stream restoration in terms of biological improvement?

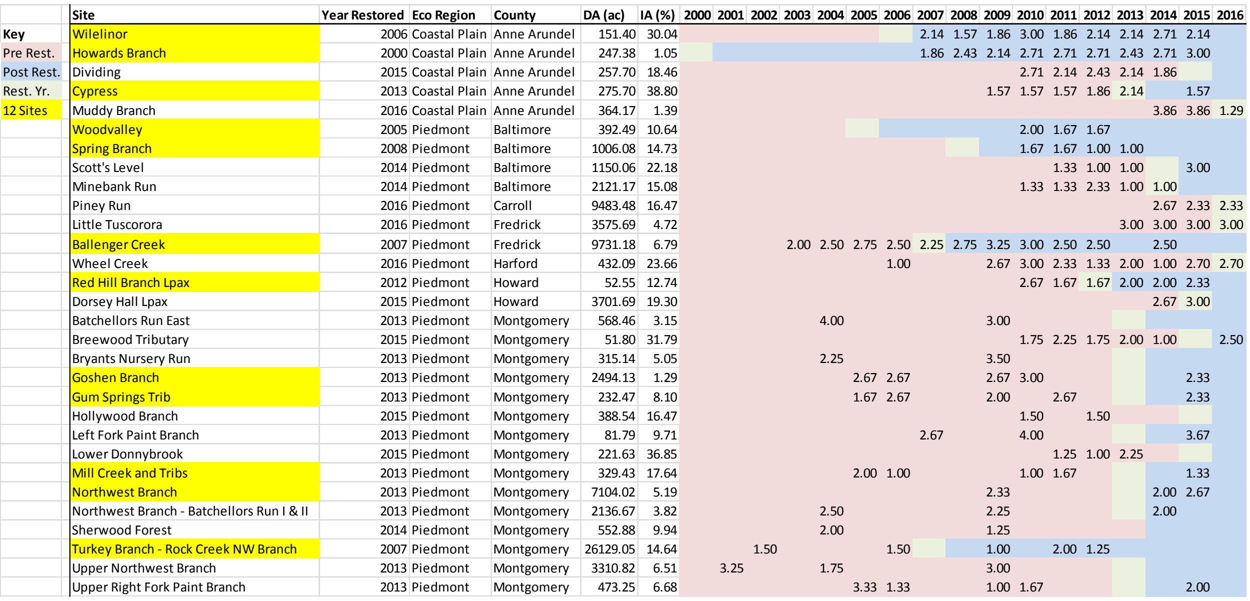
We hypothesize that the absence of high-quality biological assemblages in nearby stream reaches reduces the ability of stream restoration to improve biological condition.

3. Methodology

We solicited data from restoration sites in all the counties of central Maryland and Baltimore City. A total of 30 restoration sites were identified as having biological sampling data. Of those sites, 23 sites had been sampled post construction and 18 were sampled at least 1 year post construction. Given that biological communities are typically disrupted by construction, only those sites sampled at >=1 year post construction were used in the analysis (Table 1). After applying the constraint that all monitoring sites had to have BIBI values >=2.75, this left 15 sites available for analysis. Lack of sample size (requiring n>=3) reduced the number of sites to 12.

We obtained “reference” site data from 623 sites sampled by the MBSS and countywide biological monitoring programs to characterize biological condition at stream sites in the vicinity of the restoration sites (Figure 1). The distance between each restoration site and each reference site was calculated using GIS as the distance along the stream network using the 1:24,000-scale National Hydrographic Dataset.

Table 1. Stream restoration sites with biological monitoring data. 12 Sites with adequate post-monitoring data that were used for analysis are highlighted in yellow.



	Site	Year Restored	Eco Region	County	DA (ac)	IA (%)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Key	Wilelinor	2006	Coastal Plain	Anne Arundel	151.40	30.04								2.14	1.57	1.86	3.00	1.86	2.14	2.14	2.71	2.14	
Pre Rest.	Howards Branch	2000	Coastal Plain	Anne Arundel	247.38	1.05								1.86	2.43	2.14	2.71	2.71	2.71	2.43	2.71	3.00	
Post Rest.	Dividing	2015	Coastal Plain	Anne Arundel	257.70	18.46											2.71	2.14	2.43	2.14	1.86		
Rest. Yr.	Cypress	2013	Coastal Plain	Anne Arundel	275.70	38.80										1.57	1.57	1.57	1.86	2.14		1.57	
12 Sites	Muddy Branch	2016	Coastal Plain	Anne Arundel	364.17	1.39															3.86	3.86	1.29
	Woodvalley	2005	Piedmont	Baltimore	392.49	10.64											2.00	1.67	1.67				
	Spring Branch	2008	Piedmont	Baltimore	1006.08	14.73											1.67	1.67	1.00	1.00			
	Scott's Level	2014	Piedmont	Baltimore	1150.06	22.18												1.33	1.00	1.00		3.00	
	Minebank Run	2014	Piedmont	Baltimore	2121.17	15.08											1.33	1.33	2.33	1.00	1.00		
	Piney Run	2016	Piedmont	Carroll	9483.48	16.47															2.67	2.33	2.33
	Little Tuscorora	2016	Piedmont	Fredrick	3575.69	4.72														3.00	3.00	3.00	3.00
	Ballenger Creek	2007	Piedmont	Fredrick	9731.18	6.79				2.00	2.50	2.75	2.50	2.25	2.75	3.25	3.00	2.50	2.50		2.50		
	Wheel Creek	2016	Piedmont	Harford	432.09	23.66							1.00			2.67	3.00	2.33	1.33	2.00	1.00	2.70	2.70
	Red Hill Branch Lpax	2012	Piedmont	Howard	52.55	12.74											2.67	1.67	1.67	2.00	2.00	2.33	
	Dorsey Hall Lpax	2015	Piedmont	Howard	3701.69	19.30															2.67	3.00	
	Batchellors Run East	2013	Piedmont	Montgomery	568.46	3.15					4.00					3.00							
	Breewood Tributary	2015	Piedmont	Montgomery	51.80	31.79											1.75	2.25	1.75	2.00	1.00		2.50
	Bryants Nursery Run	2013	Piedmont	Montgomery	315.14	5.05					2.25					3.50							
	Goshen Branch	2013	Piedmont	Montgomery	2494.13	1.29						2.67	2.67			2.67	3.00					2.33	
	Gum Springs Trib	2013	Piedmont	Montgomery	232.47	8.10						1.67	2.67			2.00		2.67				2.33	
	Hollywood Branch	2015	Piedmont	Montgomery	388.54	16.47											1.50		1.50				
	Left Fork Paint Branch	2013	Piedmont	Montgomery	81.79	9.71								2.67			4.00					3.67	
	Lower Donnybrook	2015	Piedmont	Montgomery	221.63	36.85												1.25	1.00	2.25			
	Mill Creek and Tribs	2013	Piedmont	Montgomery	329.43	17.64						2.00	1.00				1.00	1.67				1.33	
	Northwest Branch	2013	Piedmont	Montgomery	7104.02	5.19										2.33					2.00	2.67	
	Northwest Branch - Batchellors Run I & II	2013	Piedmont	Montgomery	2136.67	3.82					2.50					2.25					2.00		
	Sherwood Forest	2014	Piedmont	Montgomery	552.88	9.94					2.00					1.25							
	Turkey Branch - Rock Creek NW Branch	2007	Piedmont	Montgomery	26129.05	14.64			1.50				1.50			1.00		2.00	1.25				
	Upper Northwest Branch	2013	Piedmont	Montgomery	3310.82	6.51		3.25			1.75					3.00							
	Upper Right Fork Paint Branch	2013	Piedmont	Montgomery	473.25	6.68						3.33	1.33			1.00	1.67					2.00	

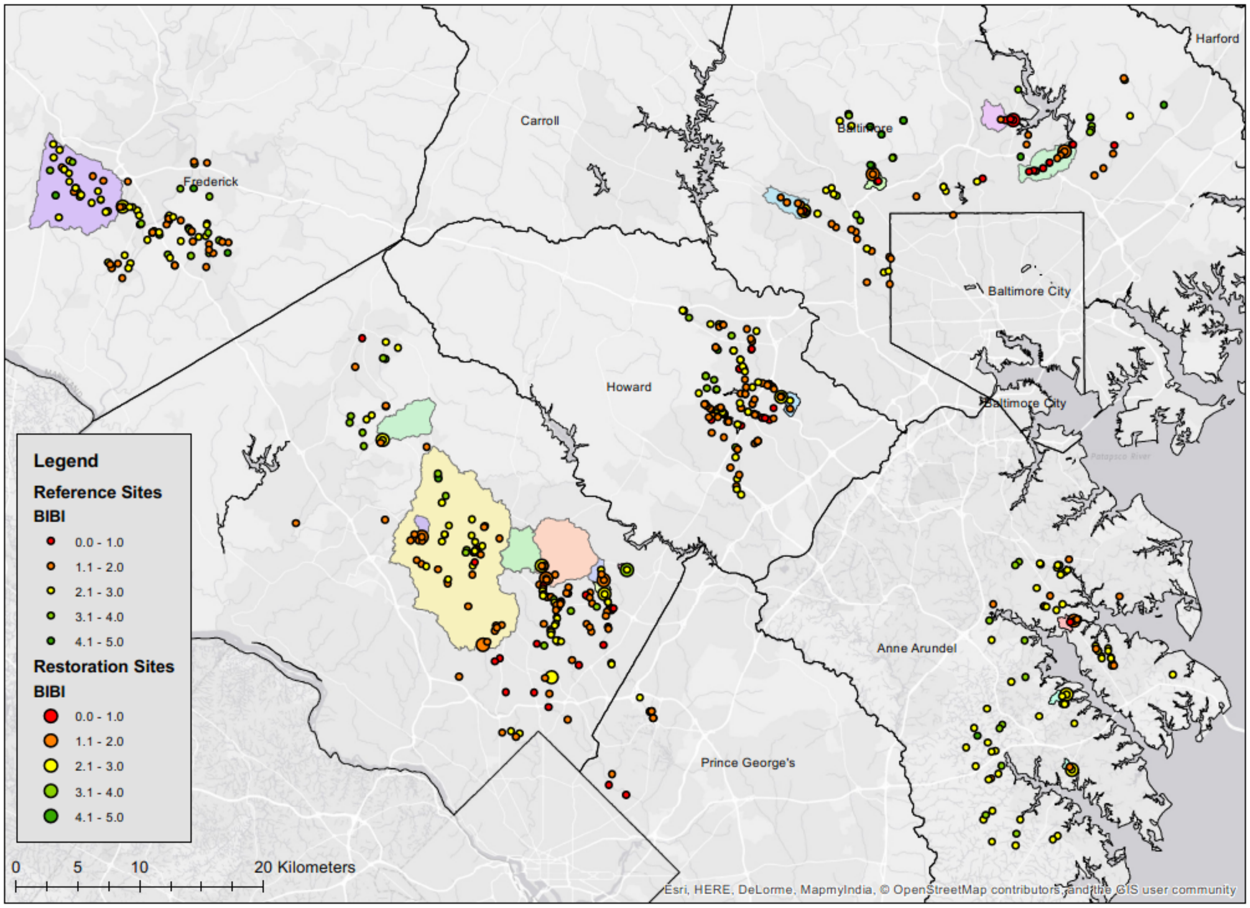


Figure 1. Stream restoration sites with adequate post-construction biological monitoring data, their watersheds, and the reference sites used for analysis.

All restoration and reference sites had been sampled for benthic macroinvertebrates using the MBSS methods (Stranko et al. 2015) and MBSS indicators (Southerland et al, 2007), except for the Montgomery County sites which were sampled and assessed with similar methods and indicators created prior to the MBSS. Previous studies have demonstrated the comparability of the MBSS and Montgomery County methods at the level of the Benthic Index of Biotic Integrity (B-IBI) and its component metrics (Roth et al. 2001). For the purposes of this study, the Montgomery County B-IBIs were converted to the MBSS scale of 1 to 5 scoring. The MBSS and Montgomery County B-IBIs are based on ecoregional reference sites characterizing least disturbed conditions.

The biological condition of streams is influenced by a myriad of natural and anthropogenic factors in the riparian and watershed areas of the sampling site. The natural factors of ecoregion and stream size (catchment area draining to the site) were calculated for each site. Data on water quality and habitat varied among sites so were not included in the analysis.

The amount of pre- and post-construction biological monitoring data varied widely among sites and increases in B-IBI post-construction were apparent at only 5 sites. Therefore, we evaluated the relationship of B-IBIs, sampled >=1 year post construction.

The B-IBI score of each restoration site was compared to the score of reference sites present at varying distances along the stream network. The metric of Ephemeroptera-Plecoptera-Tricoptera (EPT) was also investigated but did not reveal any discernable relationships. A B-IBI score of 2.75 (comparable to reference within a margin of error as codified in impaired waters listings) was designated as good biological condition. Specifically, we

- Identified reference sites within a 15-km radius of the restoration site
- Calculated shortest along-network (typological) distance between the restoration site and each reference site
- Calculated the difference in B-IBI scores ($BIBI_{ref} - BIBI_{rest}$)
- Regressed the degree of difference in B-IBI scores against typological distance

If restoration sites with closer good reference sites show better condition, we expect a positive slope as shown in Figure 2 below.

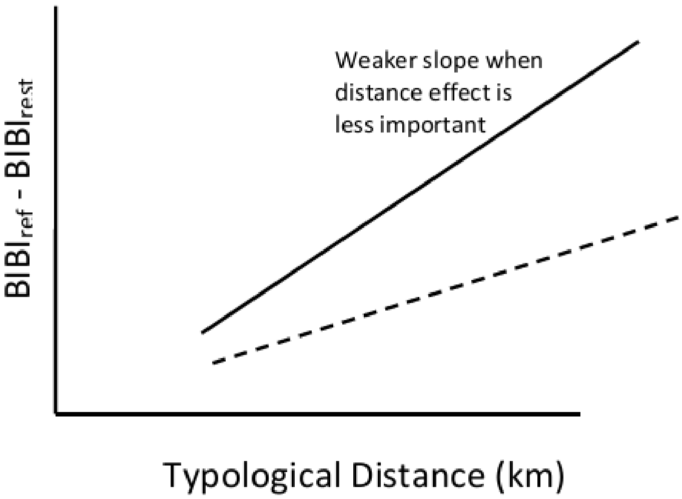


Figure 2. Difference in B-IBI scores (BIBIref – BIBIrest) regressed against typological distance

Complicating this approach is the time when reference site samples were taken relative to when the restored sites were sampled. To handle this, we added the effect of the difference in time sampled to the mixed-effects model regression assessing the sites effects, effect of distance, area draining to each sites, and interactions. Non-significant factors were removed to create the most parsimonious model. Subsequently, we investigated the effects of individual sites through simple linear regressions.

3. Results

We present the analysis in two parts. The first, comprehensive analysis of the difference between B-IBI reference streams (B-IBI >= 2.75) and the B-IBI of the restoration monitoring sites used a mixed-effects regression model that took into consideration (1) effect of site alone, (2) distance to monitoring sites, (3) difference in years sites were sampled, (4) drainage area of the monitoring sites, and (5) all interaction terms. Results of this analysis supported our hypothesis with significant explanatory power. The main effects of site and distance were significant and estimates adhered to our expectations (Table 2). All interactions terms were not significant and were thus eliminated from the analysis to generate the parsimonious model with $r^2=0.71$. The farther monitoring sites were away from the restored sites, the higher the difference in B-IBI scores.

To provide a more detailed picture of the site-to-site differences, a second analysis was a done as simple linear regressions of the difference between the B-IBI of reference streams (B-IBI >= 2.75) and the B-IBI of the restoration monitoring sites. This effort was employed to determine how variability in sites deviated from our predictions. Overall, the relationship followed the direction of our hypothesis in Figure 2 but the slope was not significant (p=0.5, r2=0.014; Fig. 3). At the same time, the intercept was significant (p<0.001) with a value of only 1.1, suggesting that reference sites very close to a restoration site might be important to restoration site B-IBI.

The site that conformed best to our predictions, Howards Branch, shows the strongest positive relationship ($r^2=0.88$) of proximity of good reference sites to restoration site biological condition (Figure 4). At this site, it is likely that the length of post-construction biological monitoring spanning 15 years, and inclusion of more restoration sites, improved our ability to quantify the proximity effect. To place this result into context, only 4 of 12 restoration sites showed a significant proximity effect. These 4 sites were sampled 3, 5, 7, and 15 years post construction, generally longer than the sites not showing significant effects. A comprehensive summary of the linear regression results for each of the 12 sites is given in Table 2.

SOV	Estimate	Standard Error	t	P
(Intercept)	**5.42E-01**	**1.64E-01**	**3.307**	**0.001231**
Site-Cypress	**8.61E-01**	**1.52E-01**	**5.673**	**9.11E-08**
Site-Goshen Branch	3.49E-01	1.79E-01	1.946	0.053923
Site-Gum Springs Trib	1.02E-01	2.98E-01	0.341	0.733395
Site-Howards Branch	-4.32E-01	2.37E-01	-1.822	0.070759
Site-Left Fork Paint Branch	**-1.21E+00**	**3.59E-01**	**-3.375**	**0.000983**
Site-Mill Creek and Tribs	**1.45E+00**	**1.77E-01**	**8.181**	**2.62E-13**
Site-Northwest Branch	-9.16E-02	2.18E-01	-0.42	0.674883
Site-Red Hill Branch Lpax	**4.72E-01**	**1.54E-01**	**3.068**	**0.002639**
Site-Spring Branch	**1.76E+00**	**2.03E-01**	**8.644**	**2.09E-14**
Site-Turkey Branch-Rock Creek NW	**1.06E+00**	**2.08E-01**	**5.086**	**1.29E-06**
Site-Upper R Fork Paint Branch	4.69E-01	3.59E-01	1.306	0.19401
Site-Wilelinor	**3.64E-01**	**1.80E-01**	**2.026**	**0.044836**
Site-Woodvalley	**1.89E+00**	**1.79E-01**	**10.543**	**< 2e-16**
Distance	**3.16E-05**	**1.38E-05**	**2.296**	**0.023345**
Drainage	-6.35E-06	1.39E-05	-0.457	0.648374
Years	-5.25E-03	9.48E-03	-0.553	0.581087

Table 2. Mixed-effects model regression of differences in B-IBI scores (BIBIref – BIBIrest) against sites, typological distance between restoration and reference sites, differences in year of sampling between sites, and size of drainages to sites. Multiple $r^2 = 0.71$.

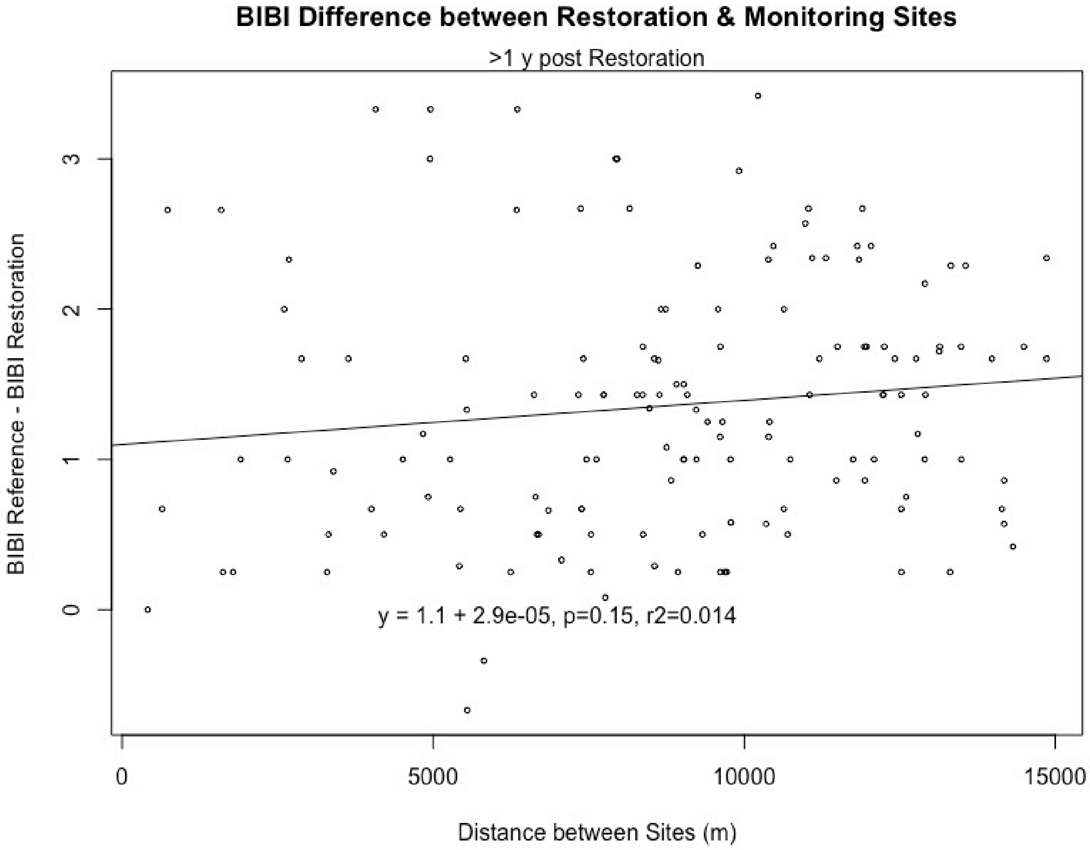


Figure 3. Linear regression of difference in B-IBI scores (BIBIref – BIBIrest) against typological distance between restoration and reference sites.

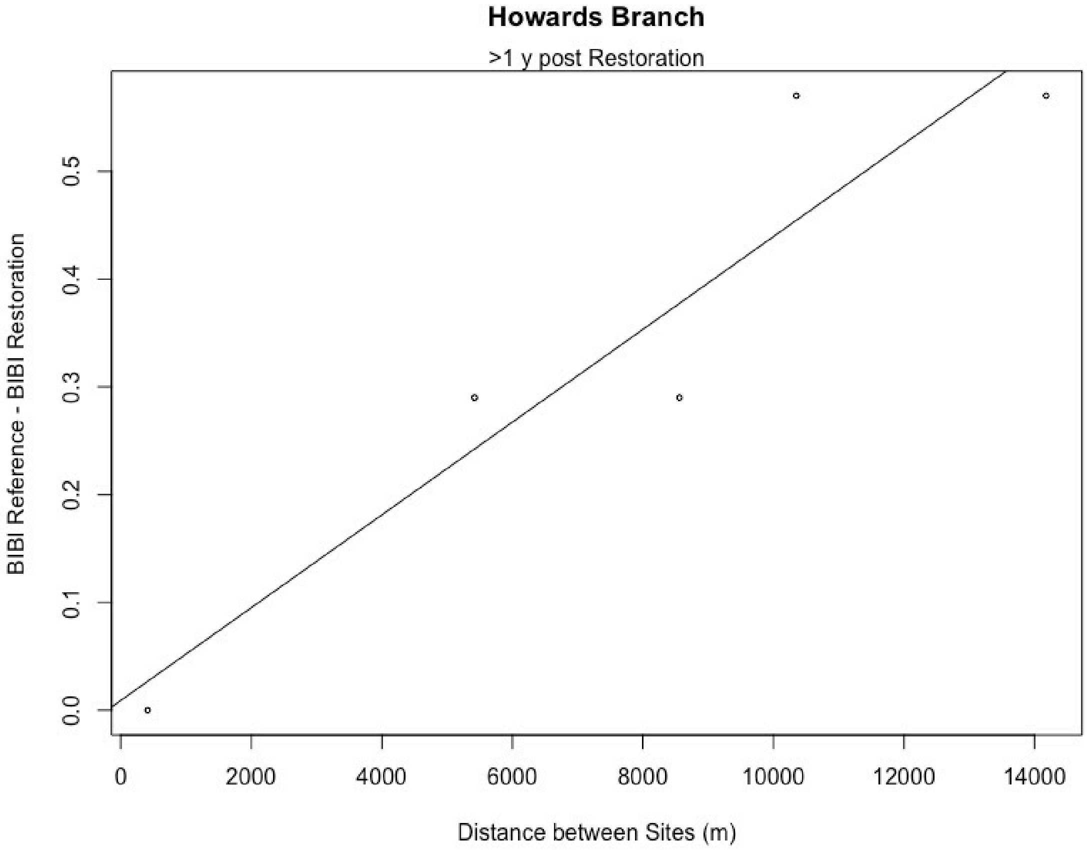


Figure 4. Linear regression of difference in B-IBI scores (BIBIref – BIBIrest) against typological distance between restoration and reference sites for Howards Branch (p=0.018, r^2=0.88).

Site	Intercept	Slope	p	r^2
Ballenger Creek	**0.22**	**6.00E-05**	**0.012**	**0.17**
Cypress	***0.88***	***8.40E-05***	***0.09***	***0.2***
Goshen Branch	1.1	-1.75E-06	0.96	0.0003
Gum Springs Trib	0.84	-1.10E-05	0.77	0.13
Howards Branch	**0.009**	**4.30E-05**	**0.02**	**0.88**
Mill Creek and Tribs	1.9	3.36E-05	0.59	0.03
Northwest Branch	0.94	-4.20E-05	0.71	0.04
Red Hill Branch	**0.21**	**1.00E-04**	**0.01**	**0.38**
Spring Branch	**3.6**	**-1.10E-04**	**0.05**	**0.55**
Turkey Branch	3.9	1.00E-04	0.43	0.12
Wilelinor	0.02	1.03E-04	0.26	0.15
Woodvalley	2.8	-5.40E-05	0.41	0.06

Table 3. Linear regression of differences in B-IBI scores (BIBIref – BIBIrest) against typological distance between restoration and reference sites, for individual restoration sites.

The power of this analysis is constrained by the number of restoration sites and the time since construction that the biological sampling has occurred. As shown in Figure 3, less than half the sites were sampled more than two years post construction. It is likely that additional years of post-construction biological monitoring would improve our ability to quantify this proximity effect.

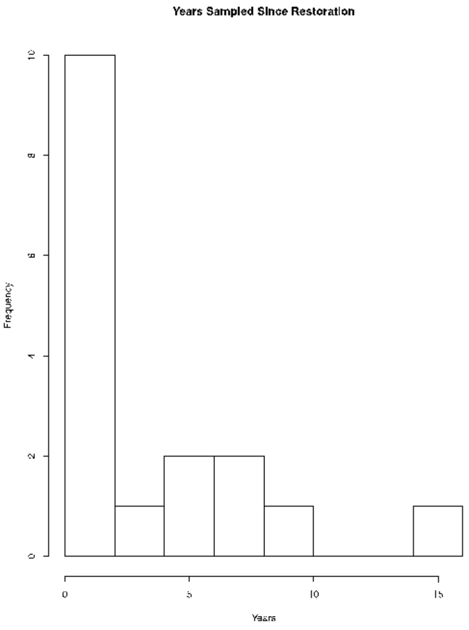


Figure 3. Number of years that restoration sites were sampled post construction

The ranges of variable values in the available data are described in the following figures. The rich dataset of reference sites was not a constraint on the analysis (Figure 4). The range of differences in the year each reference site was sampled compared to the restoration site was fairly evenly distributed from 0 to 20 years (Figure 5). The majority of catchment sizes draining to each restoration sites were less than 5000 acres, but some larger catchment sites were included (Figure 6).

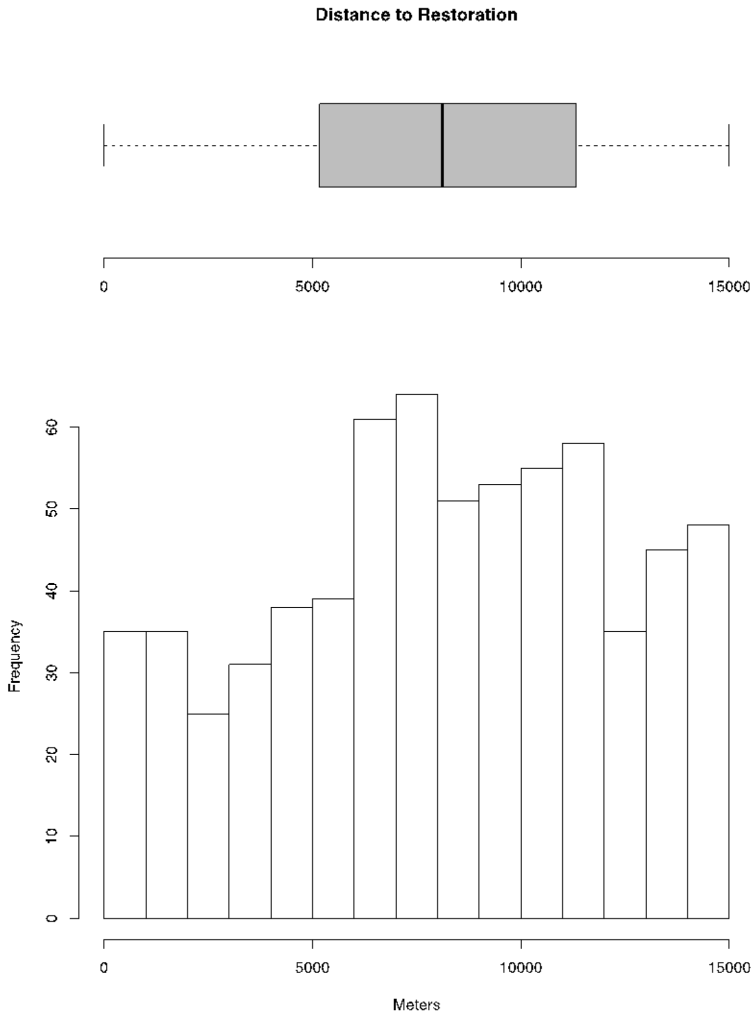


Figure 4. Distance between restoration and reference sites. Average of 8074 meters and maximum of 14,991 meters.

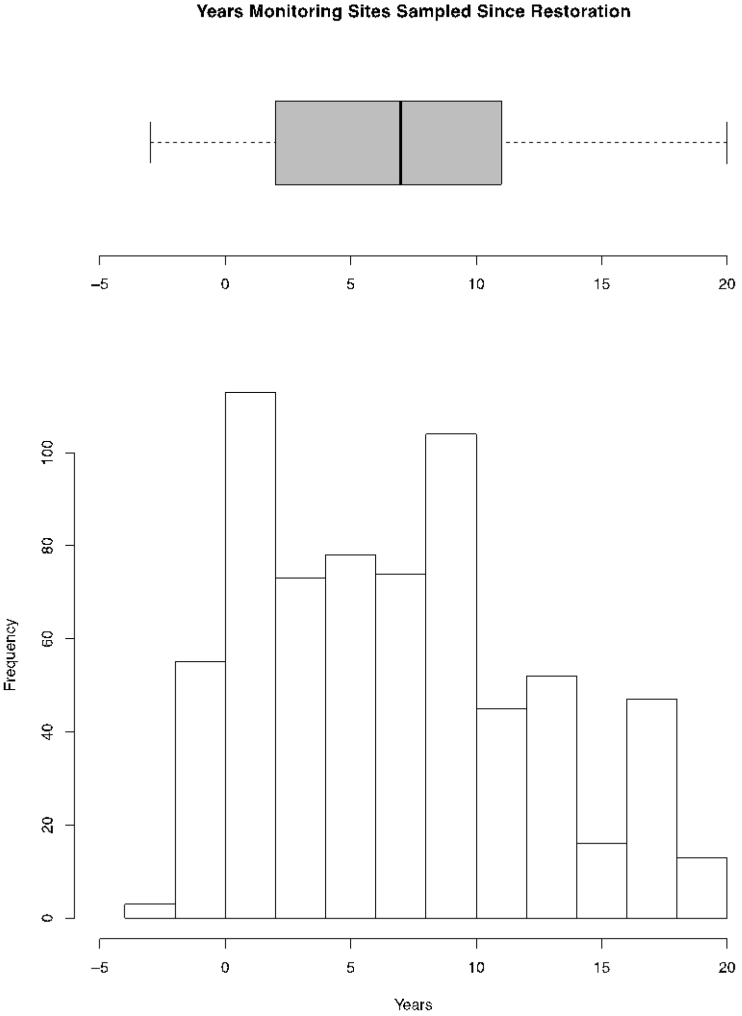


Figure 5. Difference in years sampled between restoration and reference sites. Average of 7.4 years and maximum of 20 years.

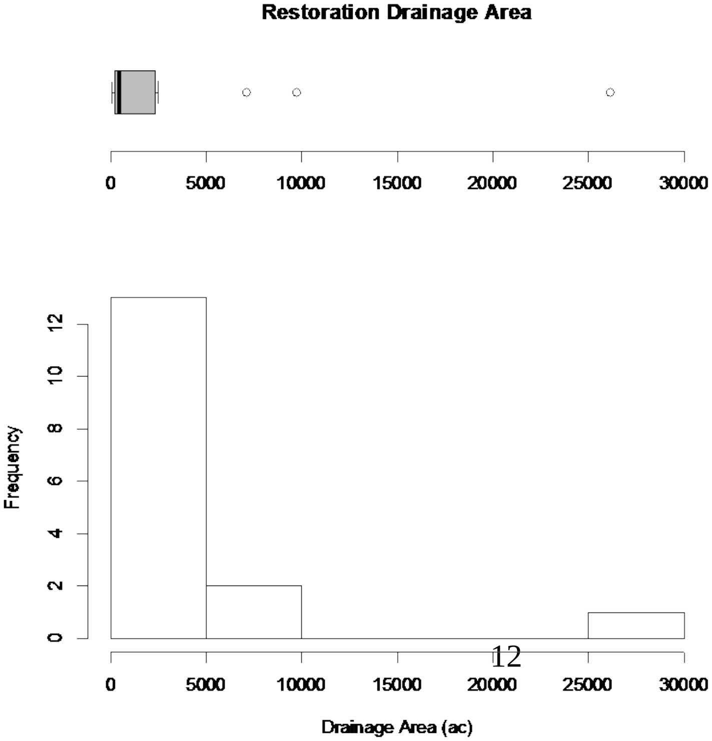


Figure 6. Catchment sizes draining to each restoration site. Average of 3762 acres, minimum of 53 acres, and maximum of 26,139 acres.

To address the limitation of the data available for this study, we propose a second phase of newly sampled sites for post-restoration biological condition that have been selected based on their proximity to stream networks that display a wide gradient of biological condition from very poor to good. We understand that the sampling conducted by Bob Hildebrand of UMCES at 40 stream restoration sites will be available later this year and could be analyzed using this approach. Beyond that, sampling could be undertaken by county partners or proposed for CBT funding in future years to create this gradient and add more Coastal Plain sites (only 3 of the 18 in this analysis were in the Coastal Plain; 15 were in the Piedmont). Additional replicates for each stream restoration type (natural channel design, regenerative stormwater conveyance, legacy sediment removal, or hybrids) could also be sampled.

Additional potentially valuable analysis not performed for this study include (1) evaluating the effects of degraded sites in the restoration site drainages that may have "blurred" any potential biological uplift offered by high quality, near-proximity sites and (2) intensive analysis of the taxon compositional data, taking into consideration taxon traits, such as dispersal capability, and the gain/loss of species.

It is hoped that our preliminary or future results will inform expectations for biological uplift from stream restoration projects. We also envision a role creating guidelines for restoration that incorporate good streams as "stepping stones" to facilitate dispersal from more remote species pools to recolonize depleted catchments.

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