TREE TRADE-OFFS IN STREAM RESTORATION PROJECTS: IMPACT ON RIPARIAN GROUNDWATER QUALITY

A Report Submitted to the Chesapeake Bay Trust

by

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<u>Introduction and Key Restoration Question(s)</u>:

Riparian zones are considered one of the most important best management practices to reduce nitrogen (N) and phosphorus (P) losses from field to streams, and ultimately the Chesapeake Bay (Lowrance et al. 1997). For decades, there has been extensive research on variables regulating the efficiency of riparian zones in improving water quality with respect to nitrate in subsurface flow, and soluble and particulate phosphorus dynamics in riparian zones *(*e.g. Lowrance et al. 1997; Mayer et al. 2007). This research stressed the role of vegetation at regulating many key riparian functions, including groundwater quality (through N and P update), soil biogeochemistry, soil erosion, streambank stabilization and the ability of riparian zones to provide habitat for wildlife (see review in Dosskey et al. 2010). However, in many cases, riparian vegetation is removed during stream restoration projects to facilitate access to the stream during construction, remove legacy sediments, or to allow for stream bank regrading to facilitate stream-floodplain interaction. In this context, vegetation removal has both immediate effects (e.g. reduced transpiration, reduced stream shading) and longer-term effects (e.g. reduced soil organic carbon). However, the impacts of tree management (years since removal, current status / survival rate) on N and P in groundwater remains poorly understood (Dosskey et al. 2010). In spite of many years of research on riparian zone water quality functions in Maryland and elsewhere, extensive field data and models to estimate the water quality impacts of tree removal are still missing, especially within the context of stream-riparian restoration projects.

A recent global review and synthesis regarding the effectiveness of stream restoration suggests that there is now more knowledge for guiding and improving restoration practices (Newcomer Johnson et al. 2016). However, these techniques may also have unintended consequences related to water quality in response to tree removal associated with decreases in nutrient uptake by vegetation and enhanced microbial decomposition of organic matter and mineralization of soil organic N and P pools. A key challenge for stream restoration practitioners is to be able to restore streams, but also to more fully understand how tree removal can influence groundwater quality. As indicated above, tree removal can occur during stream restoration to facilitate access to the stream during construction, remove legacy sediments, or to allow for stream bank regrading to facilitate stream-floodplain interaction. In order to fundamentally advance the science of stream restoration, it is therefore essential to better understand the trade-off of removing trees during the restoration process on water quality with respect to nutrients.

This project addressed the following two questions:

1) What is the impact of riparian tree removal during stream restoration and subsequent recovery (if any) on groundwater quality across restored, degraded, and forested reference sites in Maryland?

2) Which type of broadly available data are best suited to predict both the nominal and cumulative impacts of riparian zones with various history of tree dynamics / disturbance on water quality at the watershed scale?

Results from this project can allow us to help local stream restoration practitioners to prioritize riparian zone conservation by addressing how vegetation removal (disturbance associated with some types of restoration) impact groundwater quality with respect to nutrients (a common restoration goal). Our project and this report addresses the fundamental question of the impact of vegetation disturbance within the context of stream restoration on water quality. **Detailed and comprehensive results, analyses, and conclusions will be presented in (Wood et al. 2021 *Forthcoming*)**.**

Methods

To assess the impact of tree removal on riparian groundwater quality over space and time, twenty-nine shallow groundwater wells were installed across 5 sites (Campus Creek (CC), Scotts Level (SL), Paint Branch (PB), Stony Run (SR), and Minebank Run (MR)) in watersheds of the Washington D.C. and Baltimore, Maryland, USA metropolitan areas (Figure 1). Study sites encompassed a chronosequence of restoration ages (5, 10 and 20 years) as well as unrestored comparisons (Table 1). Methods for groundwater well installation and groundwater sampling were modeled after the simplified three-well method introduced and tested by Vidon and Dosskey (2008). Wells were installed in transects of three in line perpendicular to the stream, two transects per site. Well positions were categorized as "lower" (closest to the stream edge), "middle", and "upper" (farthest from the stream edge). All wells and the open stream channel in line with each transect (denoted as position "channel"), were sampled on average every 2 months over a 2-year period. All samples were analyzed on a TOC-L for dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and total dissolved nitrogen (TDN) which includes nitrates, nitrites, ammonia, and most other organic nitrogen compounds. All samples were analyzed on an ICP-OES for dissolved concentrations of B, Ca, Cu, Fe, K, Mg, Mn, Na, and S. The precision and accuracy of concentrations of all elements recorded for any given sample were ensured by reporting an average of at least three consecutive measurements from analytical instrumentation calculated based on concurrently measured calibration curves. Statistical methods used included descriptive statistics, correlation matrices, and covariance matrices calculated for the entire dataset as well as for groundwater and surface water separately.

ANOVAs were used to determine if elemental concentrations differed significantly spatially (along transects) and/or temporally (among sites of the restoration chronosequence). For this data were divided into restoration age groups "uncut" (CC & SL-uncut), "5-year cut" (PB & SL), "10-year cut" (SR) and "20-year cut" (MR) as well as position groups "channel", "lower", "middle", and "upper". Two-way ANOVAs with independent variables restoration age and position (including interactions) were performed for each of the chemical constituents (DIC, DOC, TDN, B, Ca, Cu, Fe, K, Mg, Mn, Na, and S) as the dependent variable. ANOVAs were performed on all data combined (groundwater and surface water), groundwater only, and surface water only. Linear regressions were used to investigate chemical relationships and trends in concentrations over time. A p-value of 0.05 or less was considered statistically significant.

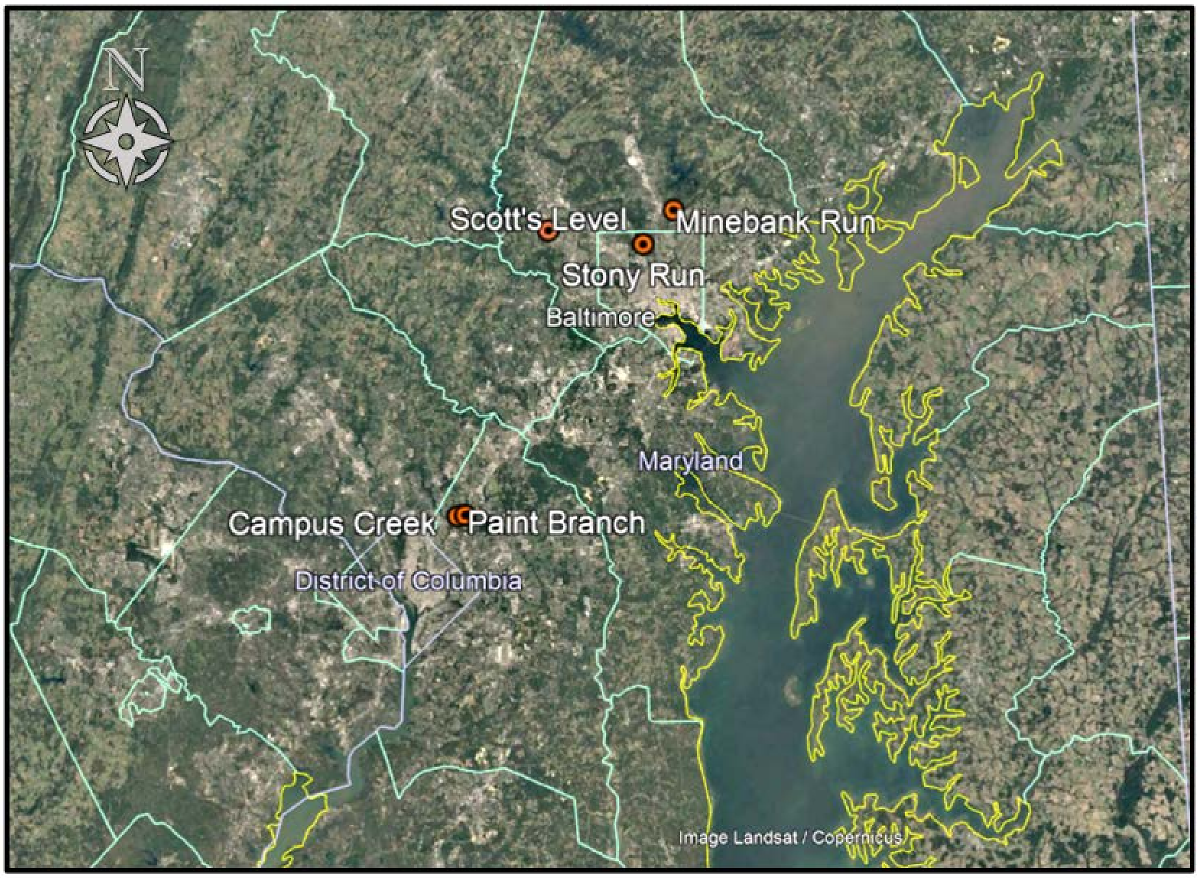


Figure 1: Site Map showing the locations of all 5 study sites in Maryland with state (yellow) and county (aqua) borders.

	Campus Creek (Uncut)	Paint Branch (5-year Cut)	Scotts Level (Uncut & 5-year Cut)	Stony Run (10-year Cut)	Minebank Run (20-year Cut)
Year restored	2019	2014	2014	2009	1999
Area of Tree Canopy Removed (km^2)	TBD	13.958	9.703	6.089	NA
Geologic Province	Coastal plain (quaternary sediments)	Coastal plain (quaternary sediments)	Piedmont (quartz feldspar schist and granulite)	Piedmont (gabbro and norite)	Piedmont (schist and gneiss)
USDA Soil Classification	ZS—Zekiah and Issue soils, frequently flooded	CF- Codorus and Hatboro soils, frequently flooded	hbA- Hatboro silt loams	50A- Hatboro-Codorus complex, frequently flooded	MmA- Melvin silt loam
Major Observed Soil Textures	Clay, gravelly clay, sandy clay, sand, silty sand	Silty sand loam, clay, gravelly coarse sand, clayey sand	Silt loam, clay, gravelly clay, sandy clay	Very gravelly silt loam	Silt loam, silty clay, silty sand, gravelly sand
Riparian Zone Slope	0.05	0.12	0.07	0.09	0.1
Riparian Zone Width (m)	32-35	40+	5-25	10-18	20-25
Channel Width (m)	2-3	10-12	2-4	2-4	1-2
NWI Wetland Classification	PFO1A Freshwater forested/ shrub wetland	PFO1A Freshwater forested/ shrub wetland	PEM5Ax- Freshwater emergent wetland PFO1Ax-Freshwater forested/ shrub wetland	R3UBH- Riverine	PFO1/EM5A- Freshwater forested/ shrub wetland
Vegetation	Mature Trees (Maple, Holly, Beech)	Herbaceous near river, Mature trees upland (Tulip Magnolia, Maple)	Transect A: Herbaceous Transect B: Mature trees (Hickory, Oak)	Young/relatively smaller trees (Redbud, Beech)	Mature trees (Sycamore, Beech, Oak) & herbaceous
Drainage Basin Area (mi^2)	0.59	29.3	1.19	0.64	0.41
Impervious Surface Cover in Watershed	22.8 %	31.6 %	37.7%	39.6%	40.8
Forest Cover in Watershed	24.9 %	25.6 %	19.9 %	12 %	25 %

Table 1: Site Attributes.

Results

Analysis of variance revealed interesting and significant differences among restoration age groups for each of the major plant nutrients (Table 2). Particularly, concentrations of DOC, TDN, K and S in groundwater were elevated (means) and/or more variable (ranges) at Paint Branch and Scotts Level, which were the two youngest restoration sites (5-year cut). Concentrations of plant macronutrients DIC, DOC, TDN, Ca, K, Mg, and S showed statistically significant differences in means among restoration ages for groundwater, surface water or for groundwater and surface water combined (Table 2). Mn, a plant micronutrient, did as well despite being less affected by tree uptake.

	Groundwater & Surface Water									Groundwater									Surface Water		
	Restoration Age			Position			Restoration Age x Position			Restoration Age			Position			Restoration Age x Position			Restoration Age		
	n	F	p-value	n	F	p-value	n	F	p-value	n	F	p-value	n	F	p-value	n	F	p-value	n	F	p-value
DIC*	259	24.212	**≤0.001**	259	5.724	**≤0.001**	259	2.723	**0.005**	186	22.27	**≤0.001**	186	1.284	0.28	186	1.316	0.253	73	17.977	**≤0.001**
DOC*	259	7.75	**≤0.001**	259	1.216	0.305	259	2.331	**0.016**	186	7.822	**≤0.001**	186	0.79	0.456	186	1.706	0.123	73	4.572	**0.006**
TDN*	259	3.731	**0.012**	259	0.89	0.447	259	3.08	**0.002**	186	3.45	**0.01**	186	2.466	0.088	186	1.662	0.112	73	19.359	**≤0.001**
B	263	0.726	0.537	263	0.865	0.46	263	0.639	0.763	187	0.489	0.691	187	1.039	0.356	187	1.149	0.337	75	0.261	0.853
Ca*	263	44.524	**≤0.001**	263	2.857	**0.038**	263	3.965	**≤0.001**	187	35.952	**≤0.001**	187	2.669	0.072	187	0.86	0.526	75	13.752	**≤0.001**
Cu	263	2.536	0.058	263	0.495	0.686	263	0.462	0.899	187	2.79	**0.042**	187	0.119	0.888	187	0.388	0.886	75	0.854	0.471
Fe	263	1.885	0.133	263	0.638	0.592	263	1.179	0.309	187	1.962	0.122	187	0.667	0.515	187	0.845	0.537	75	15.736	**≤0.001**
K*	263	2.849	**0.038**	263	2.942	**0.034**	263	5.159	**≤0.001**	187	3.083	**0.029**	187	2.654	0.074	187	6.094	**≤0.001**	75	0.269	0.848
Mg*	263	58.203	**≤0.001**	263	4.967	**0.002**	263	10.67	**≤0.001**	187	45.538	**≤0.001**	187	6.482	**0.002**	187	16.965	**≤0.001**	75	16.622	**≤0.001**
Mn	263	5.885	**≤0.001**	263	2.136	0.097	263	4.632	**≤0.001**	187	6.612	**≤0.001**	187	1.564	0.212	187	3.463	**0.003**	75	7.556	**≤0.001**
Na	263	1.456	0.228	263	5.804	**≤0.001**	263	1.328	0.223	187	2.566	0.057	187	11.37	**≤0.001**	187	2.489	**0.025**	75	1.99	0.126
S*	263	4.618	**0.004**	263	0.32	0.811	263	2.238	**0.021**	187	6.366	**≤0.001**	187	0.205	0.815	187	0.622	0.713	75	4.216	**0.009**

Table 2: Two-way Analysis of Variance (ANOVA) results for each chemical constituent with independent variables set as site restoration age (Uncut, 5-yr Cut, 10-yr Cut, or 20-yr Cut) and sampling position (Channel, Lower, Middle or Upper) as well as interactions. ANOVA performed on groundwater (Lower, Middle and Upper) and surface water (Channel) combined and separately. (*) Indicates a major plant nutrient. Significant p-values are bolded and underlined.

Tukey's analyses of elemental mean concentrations in groundwater based on restoration age revealed among which restoration age groups significant differences were observed (Table 3). The most recently restored (5-year cut) riparian zones showed greater ranges in concentrations of TDN, DOC and S than uncut riparian zones (Figure 2). Paint Branch was more consistently elevated than Scott's Level which may be due to more extreme hydrologic conditions at Paint Branch which drains a larger watershed. Uncut sites had groundwater TDN concentrations averaging 0.75 mg/L and ranging only 0-2.62 mg/L. In contrast, the 5-year cut sites averaged 2.54 mg/L TDN and showed much more variability ranging 0- 20.5 mg/L. DOC concentrations showed significant differences between age groups; at uncut sites concentrations averaged 4.74 mg/L and ranged only 0.74-18.53 mg/L; while DOC concentrations at the 5-year cut sites averaged 9.13 mg/L and ranged 1.47- 51.92 mg/L. Similarly, sulfur concentrations were lowest at the uncut and 20-year cut sites and most elevated at the 5-year cut sites. Ranges in K concentrations at 5-year cut sites were greater but means did not vary largely through age groups. Uncut sites showed a range in K concentrations of 0.24-7.12 mg/L, whereas 5-year cut sites showed a range 0.01-15.4 mg/L.

	DIC			DOC			TDN			Ca		
	Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*
Uncut	14.931	4.155	a	4.742	0.831	a	0.752	0.326	a	14.483	3.409	a
5-yr cut	42.186	4.753	b	9.126	0.95	b	2.535	0.373	b	48.118	3.926	b
10-yr cut	68.235	8.913	c	3.576	1.782	a	0.867	0.699	a,b	70.389	7.465	c
20-yr cut	64.384	5.406	c	2.657	1.081	a	1.5	0.424	a,b	65.281	4.539	c
	K			**Mg**			**Na**			**S**		
	Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*
Uncut	2.746	0.253	a	4.625	1.028	a	6.283	0.855	a,b	4.166	0.732	a
5-yr cut	3.777	0.291	a	8.691	1.184	b	8.435	0.985	a	7.143	0.843	b
10-yr cut	3.958	0.553	a	11.554	2.252	b	7.468	1.873	a,b	5.534	1.602	a,b
20-yr cut	3.5	0.336	a	24.751	1.414	c	4.357	1.139	b	1.63	0.974	a

Table 3: Tukey's (*post-hoc) results from restoration age-based ANOVA. For each chemical constituent, restoration ages that share a letter (a, b, etc), mean concentrations are not significantly different. Those that do not share a letter are significantly different.

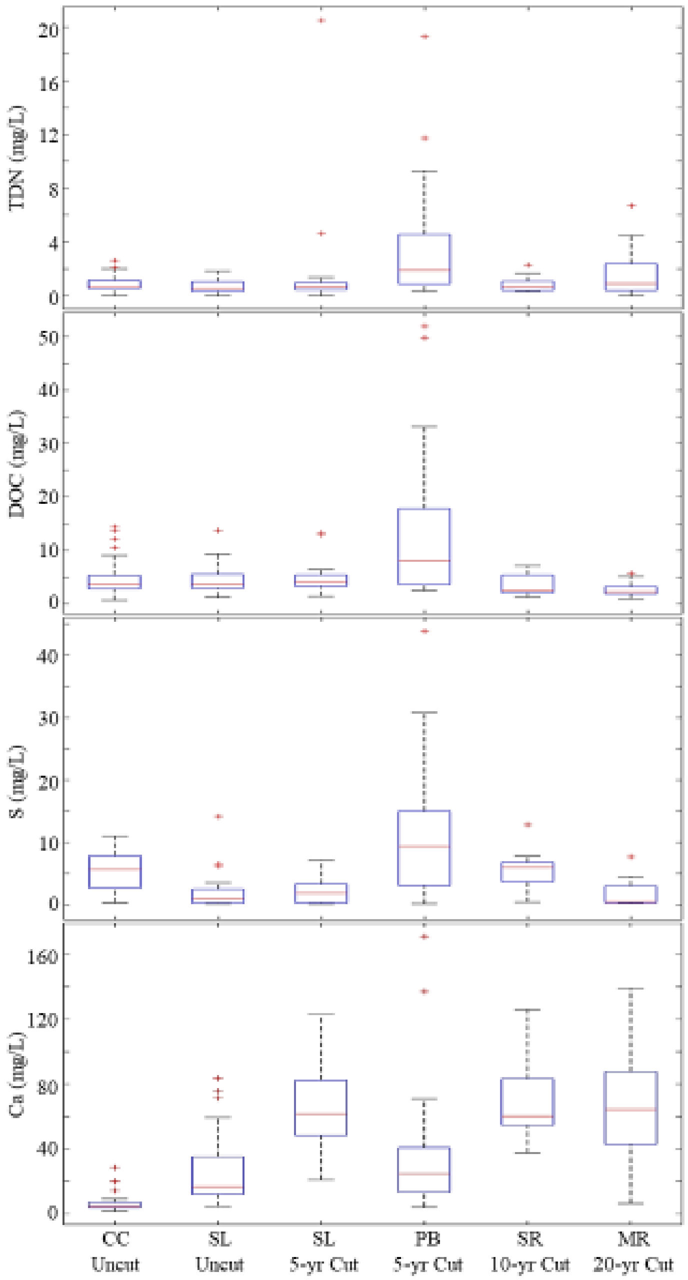


Figure 2: Box and whisker plots showing groundwater concentrations of TDN, DOC, S, and Ca by site and restoration age.

Patterns in mean Ca concentrations across the chronosequence were very similar to patterns and mean concentrations of DIC (Table 3) suggesting a relationship between Ca and DIC (Figure 3), perhaps in the form of calcium carbonate. Observed groundwater Ca, DIC, and Mg concentrations were greater at the riparian sites located in the piedmont province, which consists of various types of metamorphic lithologies that contain mafic minerals (Mg-rich) and marble (Ca and DIC). Na concentrations were significantly higher at the 5-year cut than the 20-year cut sites, but patterns across other sites were likely obscured by anthropogenic sources like road salts.

Overall, there were shifts in mean and maximum values of DOC, TDN, K, and S with consistent peaks at 5-year cut sites and declines to pre-disturbance concentrations over longer time scales.

Significant elemental correlations with carbon were also observed potentially suggesting the importance of storage and release of plant nutrients in organic matter or similarities in sources and transport (Figure 5). The correlation between DOC and DIC was stronger at each of the 5-year cut sites than at their uncut paired comparison sites. All sites except the 10-year cut site have statistically significant (p-value < 0.005) correlations between K and DOC. Only Paint Branch (5-year cut) and Stony Run (10-year cut) have statistically significant correlations between Ca and DOC.

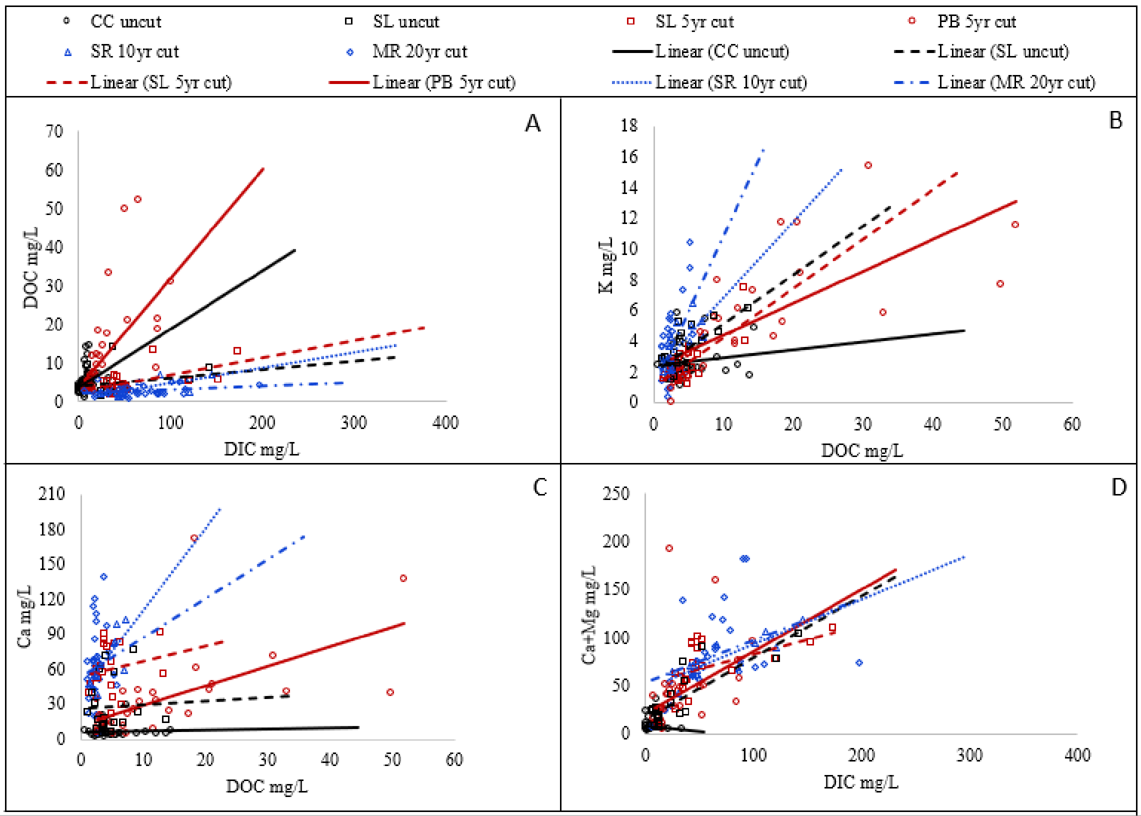


Figure 3: Chemical interactions indicative of biogeochemical processes. Scatter plot by site and restoration age with linear regressions. Regression statistics: A)DOC vs DIC [CC uncut r=0.38 /p-value=0.006; SL uncut r=0.3 /p-value=0.16 ; SL 5yr cut r=0.64 / p-value=0.001 ; PB 5yr cut r=0.62 /p-value=0.0001 ; SR 10yr cut r=0.79 /p-value=0.001 ; MR 20yr cut r=0.33 /p-value=0.033]. B) K vs DOC [CC uncut r=0.43 /p-value=0.002; SL uncut r=0.73 /p-value=0.0001 ; SL 5yr cut r=0.6 / p-value=0.003 ; PB 5yr cut r=0.65 /p-value=0.0001 ; SR 10yr cut r=0.5 /p-value=0.08 ; MR 20yr cut r=0.47 /p-value=0.002]. C) Ca vs DOC [CC uncut r=0.05 /p-value=0.72; SL uncut r=0.06 /p-value=0.79 ; SL 5yr cut r=0.25 / p-value=0.26 ; PB 5yr cut r=0.58 /p-value=0.001 ; SR 10yr cut r=0.81 /p-value=0.001 ; MR 20yr cut r=0.09 /p-value=0.59]. D) Ca + Mg vs DIC [CC uncut r=0.39 /p-value=0.005; SL uncut r=0.71 /p-value=0.0002 ; SL 5yr cut r=0.56 / p-value=0.006 ; PB 5yr cut r=0.41 /p-value=0.02 ; SR 10yr cut r=0.91 /p-value=0.00002 ; MR 20yr cut r=0.34 /p-value=0.03]

The sampling period of this study covered significant changes in hydrologic conditions; in 2018 there was a total of 1,824.7 mm of precipitation, which was about twice as much as the year prior (2017 totaled 972.9 mm of precipitation) and the year following (2019 totaled 969.1 mm of precipitation) (Figure 4). All sites, regardless of restoration age, showed a decline in dissolved concentrations of some chemical constituents through the sampling period which shifted from wet to dry conditions. TDN, K, and S in groundwater show statistically significant (p-value < 0.0001) declining linear trends (Figure 5). In contrast, Na, which is not a plant macronutrient and may be considered a conservative tracer, did not show any statistically significant trend (p-value= 0.6045), as could be expected as it is not under as much plant biological demand. There were some exceptionally high values of concentrations of N and K during the wet year at the 5-year cut sites (Figure 5), where there could have been flushing of nutrients due to lack of tree uptake.

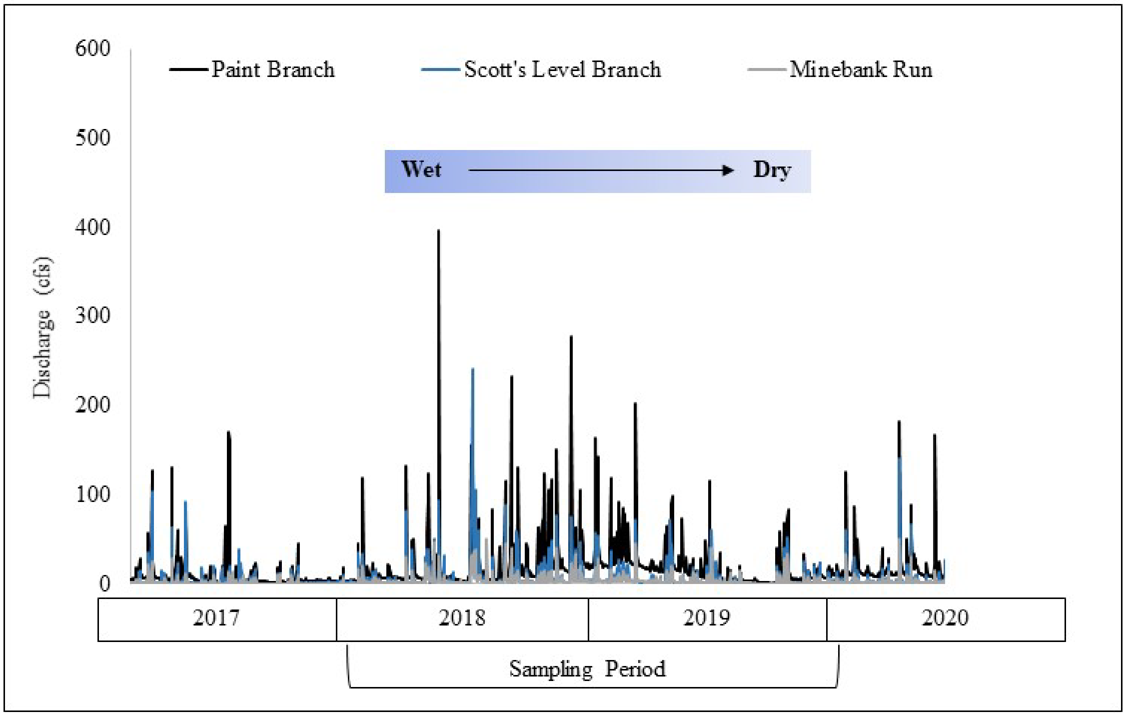


Figure 4: Hydrograph showing daily discharge (cubic feet per second, cfs) as measured by USGS stream gauges located in Paint Branch (upstream of site), Scotts Level (downstream of site), and Minebank Run (downstream of site). Publicly available data obtained via waterdata.usgs.gov.

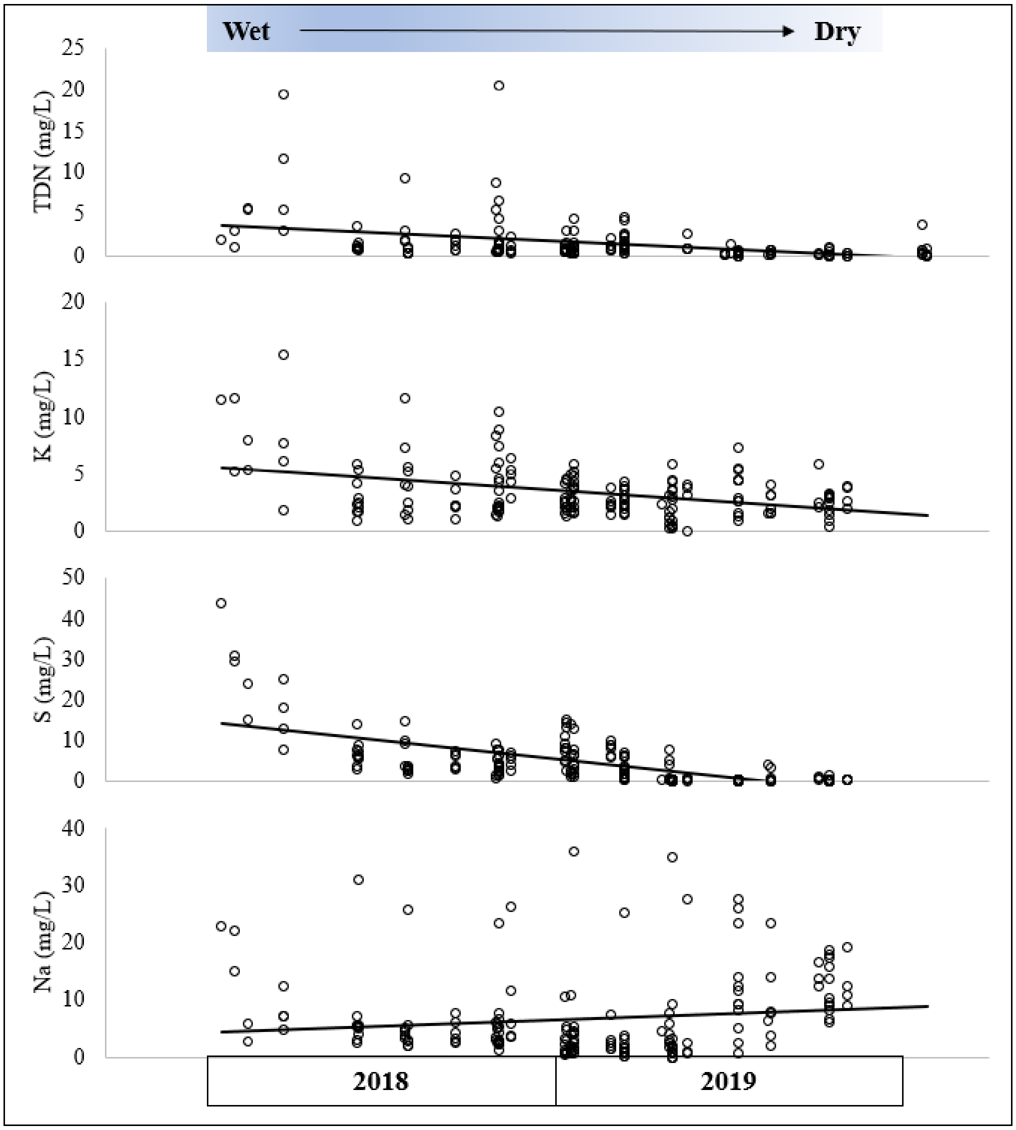


Figure 5: Timeseries of all groundwater data (all sites combined) trends from wet to dry conditions (refer to Figure 3). Regression statistics: [TDN r=-0.37 / p-value= <0.00001; K r=-0.38/ p-value=<0.00001; S r=-0.65/ p-value=<0.00001; Na r=0.04/ p-value=0.6045].

There were also statistically significant relationships between carbon and a few plant nutrients with water table depth at the uncut sites (Figure 6). Concentrations of nutrients which were most strongly related to carbon (*e.g.*, K, N, and Ca) and most concentrated in plant biomass increased in concentrations towards the soil surface at some uncut sites; statistically significant relationships were not consistent across all sites.

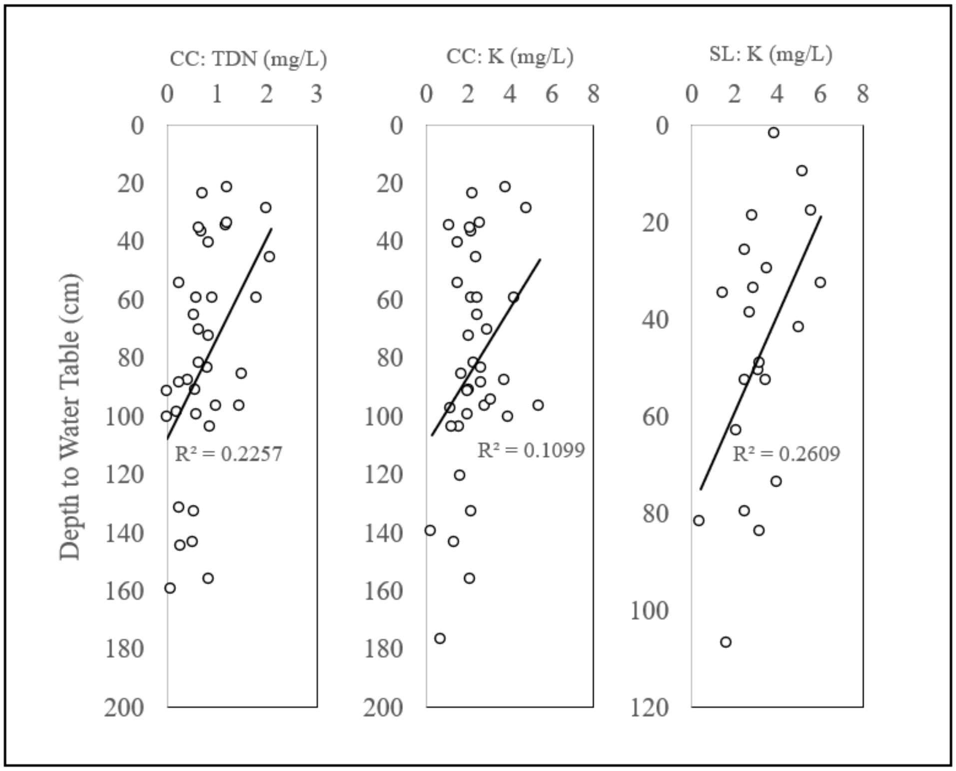


Figure 6: Relationships between nutrients and water table height at uncut sites Campus Creek (CC) and Scott's Level (SL). (p-value < 0.05)

Dissolved concentrations of DIC, Ca, K, Mg, and Na varied significantly based on position (all restoration ages combined) when considering groundwater and surface water combined; when considering just groundwater, only Mg and Na varied significantly (Table 2). However, there were significant differences in groundwater concentrations of nutrients by position when restoration ages were viewed separately. Where these concentration differences lie was determined through a Tukey's post-hoc analysis for each ANOVA (Table 4). Uncut sites did not show significant variation by position for elements DIC, DOC, TDN, Mg, Na, or S. The 5-year cut category showed more spatial variations, coinciding with the elevated and more variable nutrient concentrations. DOC and K concentrations were significantly elevated in the lower position well with mean concentrations of 13.11 mg/L and 6.04 mg/L respectively. Mean S concentrations were elevated in the lower (7.4 mg/L) and middle (8.52 mg/L) positions and lowest in the channel (2.93 mg/L). TDN was most elevated in the lower position (4.24 mg/L) and second most in the middle position (2.68 mg/L). Na was more concentrated in surface water than in groundwater at all sites regardless of restoration age possibly due to high concentrations of Na in urban runoff due to road salts. The 10- and 20-year sites showed less spatial variation similar to the uncut sites.

		DIC			DOC			TDN			Ca		
		Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*
Uncut	**Channel**	17.982	5.599	a	6.073	1.164	a	0.931	0.437	a	33.185	4.687	a
	Lower	24.395	5.848	a	4.176	1.216	a	0.574	0.456	a	28.399	4.87	a,b
	Middle	10.091	5.486	a	5.29	1.141	a	0.656	0.428	a	12.722	4.602	b
	Upper	10.308	7.082	a	4.76	1.473	a	1.025	0.552	a	10.607	5.192	b
5-yr cut	**Channel**	15.932	5.379	a	4.842	1.119	a	0.99	0.419	a,c	31.128	4.87	a
	Lower	46.066	6.465	b	13.114	1.345	b	4.238	0.504	b	56.274	5.587	b
	Middle	39.417	5.719	a,b	9.887	1.189	a	2.681	0.446	b,c	41.771	5.078	a,b
	Upper	41.075	8.674	a,b	4.376	1.804	a	0.687	0.676	c	68.729	9.204	b
10-yr cut	**Channel**	22.904	12.267	a	1.581	2.551	a	3.377	0.956	a	41.3	17.219	a
	Lower	75.798	12.267	b	2.98	2.551	a	0.707	0.956	a	78.85	17.219	a
	Middle	61.817	11.198	b	3.996	2.329	a	0.855	0.873	a	82.25	12.176	a
	Upper	67.09	15.836	b	3.752	3.293	a	1.037	1.235	a	74.367	14.06	a
20-yr cut	**Channel**	43.499	7.918	a	1.849	1.647	a	1.96	0.617	a	63.992	7.03	a,b
	Lower	55.644	7.918	a	1.858	1.647	a	1.907	0.617	a	70.658	7.03	a,b
	Middle	52.475	8.27	a	3.551	1.72	a	0.972	0.645	a	48.769	7.03	a
	Upper	85.033	7.918	b	2.562	1.647	a	1.622	0.617	a	76.417	7.03	b

		K			Mg			Na			S		
		Mean	SE	Post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*	Mean	SE	post-hoc*
Uncut	**Channel**	4.323	0.354	a	8.299	1.663	a	25.837	10.959	a	4.358	1.084	a
	Lower	2.597	0.368	b	8.508	1.728	a	7.222	11.206	a	4.136	1.108	a
	Middle	3.043	0.348	b	3.871	1.633	a	4.922	10.512	a	3.24	1.04	a
	Upper	2.496	0.392	b	3.825	1.842	a	6.704	12.388	a	5.122	1.225	a
5-yr cut	**Channel**	4.019	0.368	a	9.103	1.728	a	92.972	10.512	a	2.925	1.04	a
	Lower	6.04	0.422	b	10.66	1.982	a	13.865	12.058	b	7.404	1.193	b
	Middle	3.272	0.384	a	8.273	1.802	a	6.276	10.959	b	8.52	1.084	b
	Upper	2.109	0.695	a	9.533	3.266	a	5.164	15.847	b	5.506	1.568	a,b
10-yr cut	**Channel**	4.325	1.301	a	11.34	6.11	a	57.583	21.457	a	7.302	2.122	a
	Lower	3.985	1.301	a	13.47	6.11	a	16.57	23.505	a	7.236	2.325	a
	Middle	3.373	0.92	a	9.383	4.321	a	3.854	19.866	a	4.442	1.965	a
	Upper	5.33	1.062	a	7.203	4.989	a	1.98	30.345	a	4.923	3.002	a
20-yr cut	**Channel**	4.032	0.531	a	30.458	2.494	a	46.45	15.173	a	3.36	1.501	a
	Lower	4.169	0.531	a	13.089	2.494	b	5.132	15.173	a	1.623	1.501	a
	Middle	4.793	0.531	a	14.443	2.494	b	2.045	15.173	a	1.499	1.501	a
	Upper	1.536	0.531	b	46.72	2.733	c	5.895	15.173	a	1.767	1.501	a

Table 4: Tukey's (*post-hoc) test results of 2-way ANOVAs (see Table 2) by position for each restoration age. For each chemical constituent and restoration age, positions that share a letter (a, b, etc.) have similar mean concentrations/ are not significantly different. Those that do not share a letter do have significantly different mean concentrations.

Concentrations along groundwater well transects showed different spatial trends for uncut sites than for recently restored sites (trees removed 5 years ago) (Figure 7). Based on topographic surveys and water table measurements, generally, water tables slope toward the stream channel, though they are variable. If we assume groundwater flow direction to be from upland toward the stream, mean concentrations by position show distinct trends at uncut and recently cut sites. Mean TDN concentrations decreased by 78.6% through the uncut riparian zones but increased by 516.9% through the recently cut riparian zones. DOC decreased by 12.3% through the uncut transects and increased by 199.7% through the 5-year cut transects. K concentrations increased by only 4.1% through the uncut transects but increased by 157.5% through the 5-year cut transects. S concentrations decreased by 19.3% through the uncut transects and increased by 34.5% through the 5-year cut transects. Based on these variations in concentrations by position, some plant macronutrients are likely assimilated into biomass at the uncut sites with mature trees but concentrated along flowpaths at the recently cut sites.

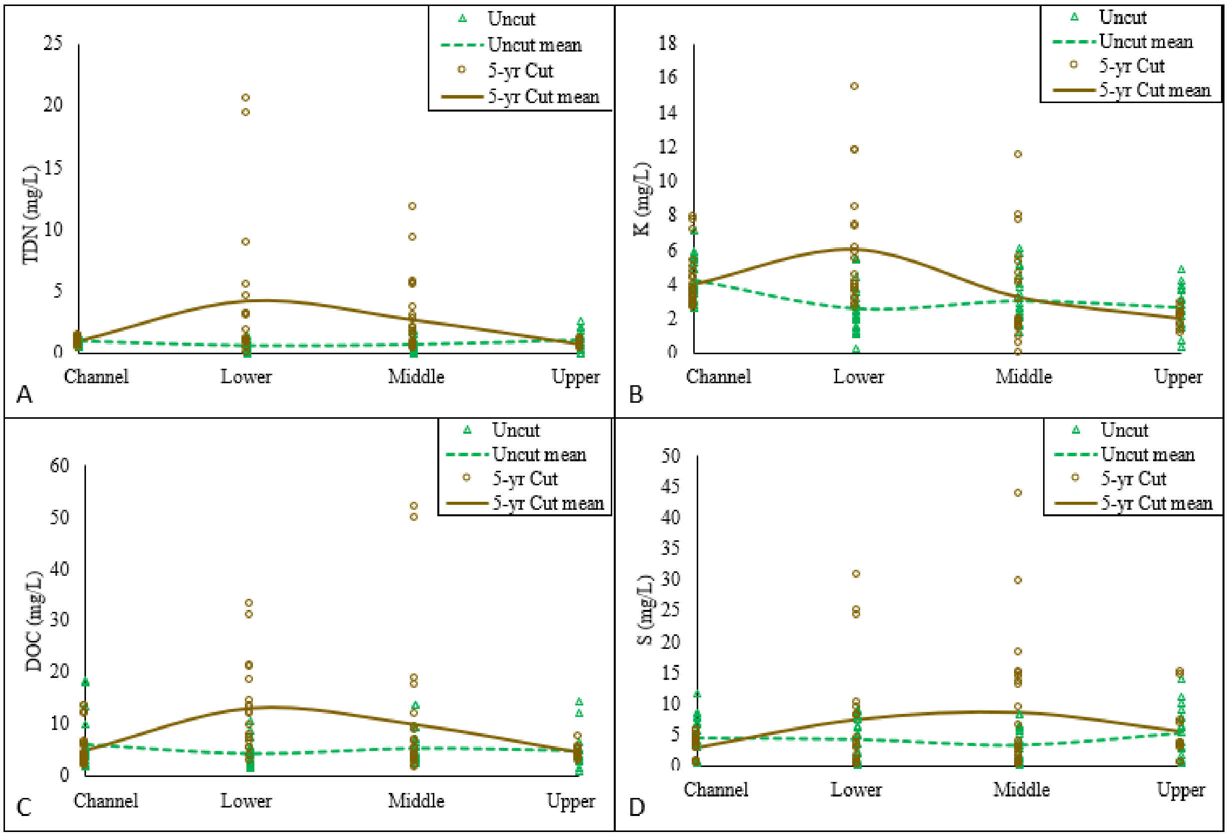
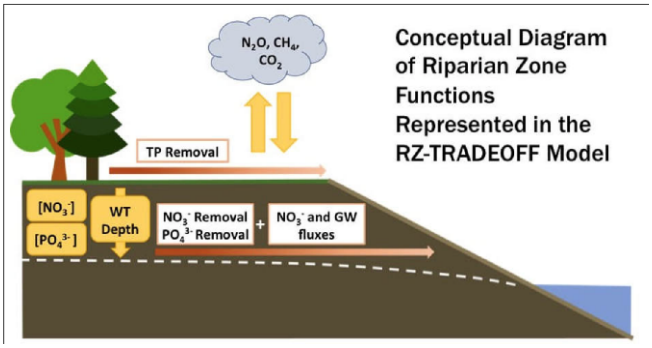


Figure 7: Plots of dissolved concentrations by position of A) TDN, B) K, C) DOC, and D) S; comparing uncut sites and 5-yr cut sites (mean concentration by position connected by curved line).

Following the completion of fieldwork and associated data analysis, we were able to apply RZ-TRADEOFF to Campus Creek, Minebank Run, Paint Branch, Scott Level, and Stony

Run experimental sites. RZ-TRADEOFF is an empirical model relying on landscape hydrogeomorphic (HGM) characteristics, land use/land cover, and weather variables to simultaneously predict NO3- and PO43-concentrations at the field edge, NO3- and PO43- subsurface removal (%), water table (WT) depth, and total phosphorus (TP) removal in overland flow, as well as CO2, CH4, and N2O emissions at the soil-atmosphere interface (Hassanzadeh et al. 2018, 2019).

In order to broaden the accessibility of this model, a user-friendly interface for RZ-TRADEOFF was created in Excel [91] for the purpose of allowing users to easily apply RZ-TRADEOFF. Model information, the RZ-TRADEOFF model, and the user interface can be accessed at https://philippevidon.weebly.com/rz-tradeoff.html. The RZ-TRADEOFF Excel interface allows the user to input attribute and weather variables and calculates the predicted values using the individual model equations. In addition, RZ-TRADEOFF provides supplementary calculations based on the model output including minimum and maximum model value for uncertainty analysis by the user, GHG output converted to CO_2 equivalents, groundwater flux, NO_3 flux, and the mass of NO_3 removed.



Based on the field data collected as part of this project, we were able to qualitatively assess the precision and accuracy of RZ-TRADEOFF with respect to water table (WT) and TN/NO3 at the 5 experimental sites for total of 4-9 dates for which field data were collected. The two tables below (Table 5, 6) highlight overall mean agreement between field data and model predictions for WT and TN/NO3 for the sampling data. A brief discission follows:

Mean WT in cm BGS	Field	Model	Qualitative Analysis of results
Campus Creek (uncut)	88	41	SATIFACTORY
Minebank Run (20 years)	70	73	EXCELLENT
Paint Branch (5 years)	160	94	SATISFACTORY
Scott Level (5 years)	39	88	SATISFACTORY
Stony Run (10 years)	37	70	SATISFACTORY

Table 5: Mean water table (WT) in centimeter below ground surface (BGS) at the 5 experimental sites used for this study for a total of 4-9 dates per site, and associated model output.

Mean TN/NO3 in mg N/L	Field	Model	Qualitative Analysis of results
Campus Creek (uncut)	0.71	0.22	SATISFACTORY
Minebank Run (20 years)	1.91	0.24	WEAK
Paint Branch (5 years)	2.37	0.37	WEAK
Scott Level (5 years)	1.33	0.13	WEAK
Stony Run (10 years)	0.86	0.77	EXCELLENT

Table 6: Mean TN/NO3 in mg N/L at the 5 experimental sites used for this study for a total of 4-9 dates per site, and associated model output.

Results reported above were obtained using RZ-TRADEOFF uncalibrated, which should be the goal from a management standpoint. Indeed, if managers have to go in the field and collect two years of data at a site and then calibrate the model for that site, then this defeats the purpose of an easy-to-use management model. We also used categories (Satisfactory, Weak, Excellent) to assess the model efficiency as we believe this type of indicator is best suited for management.

We are however in the process of testing the benefit of a regional calibration at these MD sites (and at others in NC and RI) to better understand to what extent RZ-TRADEOFF can be used as a quick assessment tool of riparian functions for management. A more quantitative analysis of model fit is in progress.

Summary of Results

Overall, results suggest that tree removal during stream restoration projects can disrupt multiple elemental cycles and shift the nutrient source or sink dynamics of riparian zones. This study also shows that there is an ecosystem recovery period following tree removal that lasts at least 5 years. As mentioned previously, it is realistically difficult to find urban riparian sites with the same exact soils, topography, and land use within our study region. All of these factors may contribute variability in results and obscure findings over space and time. However, we found statistically significant differences along sites of the chronosequence using a variety of methods, particularly among the paired 5-year cut and uncut sites in the same watersheds similar to other studies. In particular, the most bioreactive elements and organic carbon showed clear and interesting patterns such as: (1) significantly increased concentrations in riparian groundwater for at least 5 years following tree removal then subsequent recovery; (2) increased concentrations during wet periods and decreased concentrations during dry periods; (3) strong relationships with DOC (organic matter) across sites suggesting the importance of plant uptake and biomass as sources and sinks of nutrients; (4) significant increases in concentrations along hydrologic flow paths from uplands to streams in riparian zones where trees were recently cut, and opposite patterns where trees were not cut. While there are many ecosystem functions and biogeochemical interactions that could result in these chemical patterns, consistent and similar patterns in concentrations of carbon and plant macronutrients across space and time suggest the importance of trees in water quality functions of riparian zones. **Detailed and comprehensive results, analyses, and conclusions will be presented in (Wood et al. 2021 *Forthcoming*)**.**

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