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A new approach to generalizing riparian water and air quality function across regions

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Abstract There is growing interest in generalizing the impact of hydrogeomorphology and weather variables on riparian functions. Here, we used RZ-TRADEOFF to estimate nitrogen, phosphorus, water table (WT) depth, and greenhouse gas (GHG: N_2O, CO_2, CH_4) functions for 80 riparian zones typical of the North American Midwest, Northeast (including Southern Ontario, Canada), and Mid-Atlantic. Sensitivity to weather perturbations was calculated for temperature and precipitation-dependent functions (CO_2, phosphate concentration, and water table), and multivariate statistical analysis on model outputs was conducted to determine trade-offs between riparian functions. Mean model estimates were 93.10 cm for WT depth, 8.45 mg N L^{-1} for field edge nitrate concentration, 51.57% for nitrate removal, 0.45 mg PO_4^{3-} L^{-1} for field edge phosphate concentration, 1.5% for subsurface phosphate removal, 91.24% for total overland phosphorus removal, 0.51 mg N m^{-2} day^{-1} for N_2O flux, 5.5 g C m^{-2} day^{-1} for CO_2 fluxes, and − 0.41 mg C m^{-2} day^{-1} and 621.51 mg C m^{-2} day^{-1} for CH_4 fluxes in non-peat sites and peat sites, respectively. Sites in colder climates were most sensitive to weather perturbations for CO_2, sites with deep water tables estimates had the highest sensitivity for WT, and sites in warm climates and/or with deep confining layers had the lowest sensitivity for phosphate concentration. Slope, confining layer depth, and temperature were the primary characteristics influencing similarities and trade-offs between sites. This research contributes to understanding how to optimize riparian restoration and protection in watersheds based on both water (nitrogen, phosphorus) and air quality (GHG) goals.

Keywords Riparian · Nitrate · Phosphate · Greenhouse gases · RZ-TRADEOFF

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Introduction

Over the past few decades, a wide body of literature has documented the impacts of riparian zones at regulating the movement of contaminants from terrestrial to aquatic environments (Peterjohn and Correll 1984; Jordan et al. 1993; Hill 1996; Dosskey 2001). In particular, there has been a keen interest among watershed managers in using vegetated riparian zones as best management practices (BMPs) to reduce nitrate (NO_3^-) loading from agricultural areas into surface waters (Daniels and Gilliam 1996; Dosskey 2001). However, research has shown that there is variability in the NO_3^- removal capacity of riparian zones that is largely dependent on hydrogeomorphic characteristics (Gold et al. 2001; Sabater et al. 2003). For instance, riparian sites with shallow confining layers tend to direct ground water flow paths closer to the biologically active surface soils and thus increase denitrification and NO_3^- removal (Devito et al. 2000; Vidon and Hill 2004a; Maître et al. 2005). Other characteristics noted to influence riparian NO_3^- removal are upland geology, soil texture, slope, and upland aquifer size (Vidon and Hill 2004a).

Riparian zones also influence other factors such as phosphorus (P) cycling and removal. In general, riparian zones are considered to be less effective at phosphate (PO_4^{3-}) removal in the subsurface than NO_3^- removal (Dillaha et al. 1988). In addition, wide variability in PO_4^{3-} removal in riparian zones has been observed in many studies. For instance, Liu et al. (2014) observed more than a 10-fold increase in PO_4^{3-} concentrations in riparian subsurface flow compared to the field edge at one site, and a 50% reduction below field edge concentrations at another. For P in overland flow, sites with low slope gradients that decrease flow velocity have been observed to retain as much as 90% of P in overland flow, while sites with steep slopes have minimal or even negative retention of P in overland flow (Dillaha et al. 1988; Zhang et al. 2010).

Riparian zones can also act as a natural source of greenhouse gases (GHGs) to the atmosphere. Greenhouse gas emissions at the soil-atmosphere interface are somewhat temperature dependent with the three dominant GHGs—nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2)—generally increasing with higher temperature (Bowden et al. 1998; Hernandez and Mitch 2006; Sha et al. 2011). In addition to temperature, hydrology and geomorphic characteristics also influence the production of GHGs in riparian zones. For instance, flooding patterns influenced by hydrogeomorphology (HGM) have been shown to be the dominant driver of nitrous oxide (N_2O) production in riparian zones (Jacinthe and Lal 2004). Similarly, in constructed riparian wetlands, intermittent flooding regimes produce less CH_4 than continuous flooding (Altor and Mitch 2006). Water table drawdowns in a peatland simulating the water table depth of a drought period significantly increase CO_2 emissions (Freeman et al. 1992), while precipitation events that raise the water table strongly reduce CO_2 flux to the atmosphere (Oberbauer et al. 1992).

One great challenge in using riparian zones to manage multiple contaminants in complex landscapes therefore lies in generalizing and understanding how various climates and HGM interact to affect water and air quality functions of various riparian zone types. Although conceptual models linking HGM to some riparian zone function exist (Lowrance et al. 1997; Gold et al. 2001; Hill 2000; Vidon and Hill 2006), these only focus on NO_3^- removal. Empirical models (Mayer et al. 2007) and process-based models such as the riparian ecosystem management model (REMM) also exist, but these similarly focus primarily on nitrogen functions. Recently, a new model (RZ-TRADEOFF) was developed for estimating water table (WT) depth, NO_3^- and PO_4^{3-} concentration at the field edge, NO_3^- and PO_4^{3-} removal in subsurface flow, and total phosphorus (TP) removal in overland flow, as well as CO_2, N_2O, and CH_4 emissions at the soil-atmosphere interface in riparian zones (Hassanzadeh et al. 2018). Here, we use RZ-TRADEOFF to evaluate riparian zones typical of the North American Midwest, Northeast (including Southern Ontario, Canada), and Mid-Atlantic region using 80 hypothetical representative riparian sites with different combinations of HGM and land use/land cover characteristics. Research goals are to (1) examine site characteristics that lead to high or low predictions for the different riparian functions, (2) identify sites that are the most sensitive to changes in temperature and precipitation, (3) determine what type of sites behave similarly with respect to the functions estimated and why, and (4) identify any trade-offs and correlated riparian zone functions for management purpose. By understanding the influence of climate and HGM on riparian functions, this work aims to aid in management decisions, such as identifying optimal restoration and protection locations of riparian zones in watersheds based on complex water and air quality goals.

Methods

RZ-TRADEOFF model overview

RZ-TRADEOFF is an empirical model relying on HGM, land use/land cover, and weather variables to simultaneously predict NO_3^- and PO_4^{3-} concentrations at the field edge, NO_3^- and PO_4^{3-} subsurface removal (%), WT depth, and total phosphorus (TP) removal in overland flow, as well as CO_2, CH_4, and N_2O emissions at the soil-atmosphere interface (Hassanzadeh et al. 2018). For CH_4, RZ-TRADEOFF includes two models, one for wet organic rich soil (peat soils in our case) hereafter referred to as "peat," and one for all other soil types. The model is available for public use at https://dataverse.harvard.edu/dataverse/esf. Four of the individual models in RZ-TRADEOFF (NO_3^- removal, N_2O emissions, CH_4 emissions, TP removal) only use static hydrogeomorphic characteristics and thus produce a single value per site regardless of the time of year. The NO_3^- concentration model uses time of year (Julian day) as a temporal variable. The models for PO_4^{3-} concentration, CO_2 emissions, and WT depth use weather variables (precipitation, temperature) as temporal variables and thus produce output that varies by date. A full description of the model and of its precision and accuracy can be found in Hassanzadeh et al. (in review).

Synthetic/representative site development

The characteristics of the hypothetical sites representative of sites commonly found in the North American Midwest, Great Lakes (including Southern Ontario, Canada), New England, and Mid-Atlantic region were selected based on riparian zone descriptions reported in the published literature (Table 1). We first selected combinations of common HGM (i.e., depth to confining layer, slope, soil types) reported to be found in each region and then added the other variables (i.e., buffer width, land cover type). Although the representative sites are ultimately hypothetical (Supplementary Table S1), they represent common types of riparian sites expected to be found in these regions. Ultimately, 20 unique synthetic sites were developed for each region for a total of 80 in the dataset. One weather station from the National Climatic Data Center Climate Data Online website located in each region was used to obtain and download representative daily temperature and precipitation values for the model (National Oceanic and Atmospheric Administration 2018). Model output was calculated for the first of each month for every year between 2007 and 2016.

RZ-TRADEOFF model output analysis

The RZ-TRADEOFF outputs analyzed here were PO_4^{3-} and NO_3^- field edge concentrations and removal, CO_2,

Table 1 Summary of studies reporting descriptions of riparian sites used as a basis for the development of the representative sites. Legend: CT, Connecticut; IA, Iowa; IL, Illinois; IN, Indiana; MD, Maryland; NY, New York; ON, Ontario; RI, Rhode Island; VA, Virginia

Source	Number of sites	Location	Region
Archibald (2010)	1	NY	Great Lakes
Clausen et al. (2000)	1	CT	New England
Cuadra and Vidon (2011)	1	IN	Midwest
Dillaha et al. (1988)	1	VA	Mid-Atlantic
Gold et al. (1998)	2	RI	New England
Gomez et al. (2016)	1	NY	Great Lakes
Harrison et al. (2011)	2	MD	Mid-Atlantic
Jacinthe et al. (2012)	2	IN	Midwest
Jordan et al. (1993)	1	MD	Mid-Atlantic
Lee et al. (2000)	1	IA	Midwest
Magette et al. (1989)	1	MD	Mid-Atlantic
Peterjohn and Correll (1984)	1	MD	Mid-Atlantic
Robinson et al. (1996)	1	IA	Midwest
Schoonover and Williard (2003)	1	IL	Midwest
Tomer et al. (2007)	1	IA	Midwest
Vidon and Hill (2004a)	4	ON	Great Lakes
Vidon et al. (2014)	1	IN	Midwest
Vidon et al. (2016)	1	NY	Great Lakes
Watson et al. (2010)	2	RI	New England
Young and Briggs (2008)	1	NY	Great Lakes

CH_4, and N_2O emissions, TP removal in overland flow, and WT depth below ground surface (bgs), as well as the mass of NO_3^- removed and the total CO_2 equivalents emitted. The model outputs were analyzed with qualitative and quantitative methods using Microsoft Excel and Statistical Analysis System (SAS Institute, Inc 2018, Cary, North Carolina). Mean output for each function across the study 10 years was calculated by site and ranked using 20–60–80th percentiles in most cases. Output for weather-dependent functions (PO_4^{3-}, CO_2, and WT depth) was also calculated with precipitation values increased and decreased by 10% and the average daily temperature increased and decreased by 2 °C to illustrate how variations in precipitation and temperature might affect these functions. The sensitivity to changes in weather was expressed by taking the difference between output calculated when the precipitation and temperature were increased and the output when the precipitation and temperature were decreased. This value was divided by the original estimate and multiplied by 100 to represent the sensitivity as a percentage of initial model outputs.

In addition, we used hierarchical cluster analysis with Ward's minimum distance method (Seyhan et al. 1985; Schot and Van Der Wal 1992; Ketchen and Shook 1996) to identify sites that behave most similarly when average values for NO_3^- concentration, PO_4^{3-} concentration, NO_3^- removal, TP removal, WT depth, and CO_2, N_2O, and CH_4 emissions were considered. The results from the cluster analysis were qualitatively compared to the site characteristics and ranked model outputs to identify variables that lead to sites being clustered together. Factor analysis with varimax rotation was used to determine which functions drove most of the variability between sites. The number of factors retained was determined based on scree plots and the percentage of variance explained by each factor (Costello and Osborne 2005).

Results

RZ-TRADEOFF model output

Water table, N and P outputs

Actual model outputs for each of the 80 modeled sites are shown in Supplementary Table S2. Briefly, average modeled WT depth across the 10 years of analysis for the 80 modeled sites ranged from 195.65 cm bgs to 4.76 cm above surface. On a day-to-day basis, daily WT depth estimates ranged from − 38.38 to 162.43 cm bgs with a median of 73.10 cm bgs for the Great Lakes sites, − 23.4 to 230.96 cm bgs with a median of 110.00 cm bgs for the Midwest sites, − 0.73 to 180.64 cm bgs with a median of 74.19 cm bgs for the New England sites, and 5.49 to 236.56 cm bgs with a median of 103.24 cm bgs for the Mid-Atlantic sites. Water table sensitivity to changes in temperature and precipitation (see "Methods") ranged from 2.4 to 29.7% with a mean of 6.70% (Table 2). With respect to groundwater fluxes, the top 20% sites with the highest 10-year mean ground water fluxes ranged from 745.12 to 5493.63 L m^{-1} day^{-1}, the middle 60% ranged from 12.58 to 703.43 L m^{-1} day^{-1}, and the lowest 20% ranged from 0 to 10.01 L m^{-1} day^{-1}. Two sites had negative groundwater flux values since they were wetland sites with above surface (negative) WT depth estimates (Supplementary Table S2).

For NO_3^- concentration at the field edge, the highest 20% of the sites (typically field edge slope sites > 10%) had 10-year mean values ranging from 14.08 to 25.00 mg N L^{-1}. The middle 60% ranged from 3.63 to 13.98 mg N L^{-1} and the lowest 20% ranged from 0.82 to 2.71 mg N L^{-1}. With respect to NO_3^- removal, 11 of the sites were estimated by the model to have 100% NO_3^- removal, while 55 had removals that were 40% or lower.

Table 2 Mean RZ-TRADEOFF output under varying temperature and precipitation conditions and sensitivity for weather-dependent functions predicted by RZ-TRADEOFF. Legend: CO_2, carbon dioxide emissions at the soil-atmosphere interface; PO_4^{3-}, phosphate concentration at the field edge; WT, water table depth below ground surface

Variable	WT (cm)	PO_4^{3-} (mg L^{-1})	CO_2 (g C m^{-2} day^{-1})
Actual mean daily temperature and precipitation	94.34	0.048	5.50
Mean daily precipitation increased by 10% and mean daily temperature increased by 2 °C	95.63	0.045	5.86
Mean daily precipitation decreased by 10% and average daily temperature decreased by 2 °C	90.40	0.052	5.06
Sensitivity	6.70%	14.45%	16.33%

The other remaining sites had NO_3^- removal estimates ranging from 40.27 to 90.11%. Many of the sites with 100% removal had shallow confining layer depths (i.e., 2 to 0.5 m at the site) and all had fertilized cropland in the immediate upland area. Thirty-five sites had high (> 1.0 g N m^{-1} day^{-1}) masses of NO_3^--N removed ranging between 1.12 and 115.72 g N m^{-1} day^{-1}. Twenty-six sites had low values (< 0.1 g N m^{-1} day^{-1}) ranging from − 3.06 g N m^{-1} day^{-1} (indicating a source of N) to 0.09 g N m^{-1} day^{-1} removed. The remaining 19 sites had mass of NO_3^--N removed values within the medium range (0.1–1.0 g N m^{-1} day^{-1}) (Vidon and Hill 2004b; Liu et al. 2014). Sites that were large nitrate sinks generally had sandy loam or loamy sand soil types at the site, while sites that were small sinks had fine soils such as silt loam and slit clay loams.

With respect to P functions, estimated PO_4^{3-} concentration at the field edge ranged from 0.029 to 0.093 mg L^{-1}, with sites with high PO_4^{3-} concentration (top 20%) typically characterized by deep confining layer depths (i.e., > 10 m), and sites with low values primarily located in the Mid-Atlantic region. Daily PO_4^{3-} values ranged from 0.025 to 0.13 mg L^{-1} with a median of 0.025 mg L^{-1} for the Great Lakes region, and from 0.025 to 0.15 mg L^{-1} L with a median of 0.06 mg L^{-1} for both the Midwest sites and New England sites. In the Mid-Atlantic region, daily PO_4^{3-} predictions ranged from of 0.025 to 0.10 mg L^{-1} with a median value of 0.025 mg L^{-1}. Phosphorus concentration sensitivity to changes in temperature ranged from 10.70 to 18.61%, with the highest sensitivity recorded for site with either very low or very high PO_4^{3-} concentrations (Table 2). For TP removal in overland flow, narrow 5 m buffers had the lowest removal value of 69.18% removal and sites with 25 m or greater buffer width had 92.76% removal or greater. PO_4^{3-} removal in subsurface flow is a constant 1.5% in the model.

GHG flux output

In RZ-TRADEOFF, the N_2O and the two CH_4 models (peat/non-peat sites) are simple univariate models driven by confining layer depth in the upland and soil type at the site, respectively. Modeled N_2O emissions therefore ranged from 0.40 mg N m^{-2} day^{-1} for sites with 0.5 m deep confining layer to 0.75 mg N m^{-2} day^{-1} for sites with 15 m deep confining layer depth. All non-peat sites were predicted to be CH_4 sinks (− 1.51 to − 0.31 mg C m^{-2} day^{-1}), while sites with peat were CH_4 sources (621.5 mg C m^{-2} day^{-1}). In RZ-TRADEOFF, modeled CO_2 fluxes are only dependent on 30-year normal temperature and 30-day antecedent temperature, and therefore did not vary within each region with values 4.70 g C m^{-2} day^{-1} for the Midwest, 9.15 g C m^{-2} day^{-1} for the Mid-Atlantic, 3.46 g C m^{-2} day^{-1} for the Great Lakes, and 4.70 g C m^{-2} day^{-1} for New England. When calculated, total CO_2 equivalent values ranged from 7.17 to 27.95 g CO_2 m^{-2} day^{-1} depending on the region, with CO_2 fluxes representing between 85 and 98% of total CO_2 equivalent emissions. The only exception to this pattern occurred for peat dominated sites where CH_4 typically contributed between 70 and 90% total CO_2 equivalent emissions. The sensitivity to weather perturbations (see "Methods") was 22.60% for the Great Lake sites, 17.08% for the Midwest sites, 16.82% for the New England sites, and 8.82% for the Mid-Atlantic sites. The average sensitivity when all sites are considered was 16.66% (Table 2).

Multivariate statistics results

Cluster analysis indicates that the clusters occurred primarily due to shared characteristics of either high CO_2 emissions, high NO_3^- concentration and/or 100% NO_3^- removal, low TP removal and/or high CH_4 emissions, or high PO_4^{3-} concentration (Table 3). In addition, factor analysis yielded four factors, which together explained about 80% of the variability in the dataset (Table 4). The first factor called "Confining layer depth" had high loading values for PO_4^{3-} concentration at the field edge, N_2O emissions, and WT depth, all functions partly depending on confining layer depth, hence the name of factor 1. The second factor called "Soil" had high loading values for CH_4 (only depending on soil type) and represents variability between peat and non-peat sites. The third factor ("Temperature") had high loading values for the temperature-dependent CO_2 estimates. Finally, the fourth factor ("Upland land use") had high loading for both NO_3^- concentration at the field edge and NO_3^- removal; two functions directly influenced by upland land use, hence the name for this factor. The communality estimates showed that at least 59–92% of the variability in these functions individually was explained by the four factors for each variable (Table 4).

Table 3 Summary illustrating results from the cluster analysis of RZ-TRADEOFF model estimates and number of sites in each cluster. Legend: CO_2, carbon dioxide emissions at the soil-atmosphere interface; CH_4, methane emissions at the soil-atmosphere interface; NO^{3-}, nitrate concentration at the field edge; PO_4^{3-}, phosphate concentration at the field edge; TP, total phosphorus removal in overland flow

Cluster labels	# of Great Lakes sites	# of Mid-Atlantic sites	# of Midwest sites	# of New England sites
High PO_4^{3-} concentration (0.06–0.09 mg L^{-1})	1	0	9	6
High CO_2 emissions	0	20	0	0
High CH_4 emissions (peat sites) and/or low TP removal	4	0	1	0
100% NO_3^- removal and/or high NO_3^- concentration (> 10 mg N L^{-1})	10	0	1	3
Other (not categorized)	5	0	9	11

Discussion

Model output validation and key site characteristics driving individual riparian functions?

The range of mean WT depths generated by the model is generally consistent with the wide range of both average and daily observed WT depths in published studies (Gold et al. 2001; Clement et al. 2003; Shilling et al. 2004; Vidon and Hill 2004c; Liu et al. 2014). The analysis of model outputs showed that sites with deep confining layer depths of 8 to 15 m typically have deep average WT depth compared to those with shallow confining layers. This is consistent with our current understanding of how geomorphology impacts riparian water table (Lowrance et al. 1997; Hill 2000; Liu et al. 2014). Additionally, data indicate that warmer temperatures such as those typical of the Mid-Atlantic region, as well as lower precipitation, resulted in deeper WT values, which is consistent with observations showing that decreased lateral flow and increased evapotranspiration in the summer months increase WT depth by as much as 2 m (Groffman et al. 2002; Shilling et al. 2004; Jaynes and Isenhart 2014). Similarly, model outputs for groundwater fluxes are consistent with those reported in the literature, with sites with deep confining layer depth (5–15 m) and steeper slopes (5–20%) having high groundwater fluxes, and those with flat topography and shallow confining layer depth having smaller fluxes (Vidon and Hill 2004c). However, while most of the

Table 4 Summary of the factor analysis conducted on the RZ-TRADEOFF model output for the representative riparian sites. Legend: CH_4, methane emissions at the soil-atmosphere interface; CO_2, carbon dioxide emissions at the soil-atmosphere interface; NO^{3-} removal, percent nitrate removal in subsurface flow; NO^{3-}, nitrate concentration at the field edge; N_2O, nitrous oxide emissions at the soil-atmosphere interface, PO_4^{3-}, phosphate concentration at the field edge; PO_4^{3-} removal, phosphate removal in subsurface flow; TP, total phosphorus removal in overland flow; WT, water table depth below ground surface. Italic characters indicate variables most significantly related to each factor

Factor name	Factor 1 Confining layer depth factor	Factor 2 Soil factor	Factor 3 Temperature factor	Factor 4 Upland land use factor	Communality
NO_3^-	0.04	− 0.14	0.26	*0.75*	0.65
PO_4^{3-}	*0.89*	− 0.01	− 0.36	− 0.08	0.92
N_2O	*0.84*	− 0.21	0.03	− 0.11	0.77
CO_2	− 0.08	− 0.14	*0.94*	0.15	0.94
CH_4	− 0.04	*0.86*	− 0.11	0.05	0.76
NO_3^- removal	− 0.25	− 0.05	− 0.07	*0.76*	0.65
WT	*0.72*	0.18	0.5	− 0.07	0.81
TP removal	0.06	− 0.70	0	0.30	0.59
% variance explained	0.28	0.23	0.15	0.11	

flux calculated by RZ-TRADEOFF fall within or slightly above the range reported by Vidon and Hill (2004c), fluxes for sites in the highest 20% had substantially greater values. Darcy's law (used in RZ-TRADEOFF to calculated ground water flux) is by nature extremely sensitive to hydraulic conductivity. These higher than expected values were all estimated for sites with coarse soil types (sand, sandy loam, coarse sand gravel) and thus high hydraulic conductivity.

From a water quality perspective, the results of this analysis are also consistent with our understanding of the influence of topography and land cover on riparian N functions. Studies show that flat slopes in riparian zones increase denitrification by extending water residence (Gold et al. 2001; Sabater et al. 2003) and that steeper slopes increase the initial NO_3^- input from the upland area (Vidon and Hill 2004b). Similarly, the analysis for the RZ-TRADEOFF NO_3^- field edge model output shows that representative sites with highest average NO_3^- field edge concentration values had the shared characteristic of a steep edge slope (i.e., > 10% slope). In addition to having a steep edge slope, many of the modeled sites with high NO_3^- concentration estimates had fertilized cropland in the upland area. This trend is expected as agriculture is known to be a major non-point source of nitrogen pollution to freshwater systems (Carpenter et al. 1998; Dosskey 2001). Results have also documented that steeper slopes increase the mass of N removed in a riparian buffer through increased inputs from the upland area (Vidon and Hill 2004b). Our analysis of the RZ-TRADEOFF model output is consistent with these findings, since the representative sites with mass of N removed values ranked as "high" typically had high NO_3^- concentration estimates and steep edge slopes. A few sites with coarse soil types (i.e., sand, sandy loam with high hydraulic conductivity and thus high groundwater flux) but without fertilized crop in the upland or steep field edge slope were also predicted to have a large amount of N removed (> 1 g N day^{-1} per m of stream length). Overall, model outputs are consistent with literature suggesting that riparian sites with flatter slopes or forested cover in the upland can be expected to have lower NO_3^- concentration at the field edge and be smaller NO_3^- sink than those with fertilized cropland and steep slopes.

With regard to P-related functions, the range of daily PO_4^{3-} field edge concentration values predicted by RZ-TRADEOFF was also within the range of values reported by the literature (Jordan et al. 1993; Tomer et al. 2007; Liu et al. 2014). The TP removal in overland flow was 90% or higher for all the representative sites, except for the three 5 m buffers which were predicted to remove 69.1%. This is consistent with several studies showing that unless very narrow, riparian buffers are able to remove a substantial amount of TP in overland flow (Lee et al. 2000; Abu-Zreig et al. 2003; Kronvang et al. 2005). For PO_4^{3-} removal in subsurface flow, observations from the literature show that riparian zones are highly variable with regard to PO_4^{3-} removal capacity (Liu et al. 2014), and that they can act as both sinks and sources of PO_4^{3-} (Jordan et al. 1993; Daniels and Gilliam 1996). In this context, the constant mean 1.5% removal estimate given by RZ-TRADEOFF does not suggest that all riparian zones will have the same PO_4^{3-} removal efficiency, but rather that the constant provides a better estimate than predictions from a model using HGM and weather characteristics due to the wide variability in PO_4^{3-} removal capacity of riparian zones as seen in the literature.

With regard to CH_4, studies have found that non-wetland riparian zones often act as CH_4 sinks (Castro et al. 1993; Le Mer and Roger 2001; Groffman and Pouyat 2009; Gomez et al. 2016). The non-peat representative sites in this analysis with all soil types were similarly all predicted to have negative CH_4 emission values indicating that they are CH_4 sinks. Methane emissions from peat sites, meanwhile, were estimated by RZ-TRADEOFF to be a constant 621.5 mg C m^{-2} day^{-1}. While CH_4 emissions from peat sites are reported to be widely variable, the constant 621.5 mg C m^{-2} day^{-1} is within the range of observed values (Crill et al. 1988; Moore and Knowles 1989; Dise 1993; Shannon and White 1994; Turetsky et al. 2014). With respect to N_2O, values for N_2O emissions reported in the model (0.40 to 0.75 mg N m^{-2} day^{-1}) are consistent with reported mean flux values in the Northeast (DeSimone et al. 2010; Groffman et al. 2006). Several studies have noted the dependence of N_2O fluxes on topography/surficial geology, as opposed to factors such as vegetation or temperature (Clement et al. 2003; Jacinthe et al. 2012; Fisher et al. 2014). The dependence of the N_2O model on confining later depth is therefore consistent with previous work on drivers of N_2O fluxes at the riparian zone scale.

Similarly, the temperature dependence of CO_2 fluxes in RZ-TRADEOFF is consistent with other work showing the strong influence of temperature on soil respiration and CO_2 emissions from soils (Crill et al. 1988;

Bowden et al. 1998; Ullah and Moore 2011; Harper et al. 2005). The actual values for CO_2 fluxes estimated by RZ-TRADEOFF are also consistent with CO_2 fluxes reported in other studies (Ullah and Moore 2011; Morse et al. 2012; Vidon and Serchan 2016). Finally, the same thing can be said for CO_2 equivalent estimates (7.17 to 18.89 g CO_2 m^{-2} day^{-1}) (see Jungkunst et al. 2008). Importantly, although Mid-Atlantic sites exhibited the highest total CO_2 equivalent emissions for sites with non-peat soils due to warmer temperature in this region, the sites with the overall highest total CO_2 equivalent emissions were peat sites in the Great Lakes regions due to these sites having substantially higher CH_4 emissions than non-peat sites (Turetsky et al. 2014).

Which type of riparian zone is most sensitive to variability in temperature and precipitation?

Our analysis of the model results suggests that riparian sites located in areas with lower annual temperatures, such as the Great Lakes region, are the most sensitive to changes in temperature with regard to CO_2 emissions. Warming has been noted to increase soil CO_2 emissions due to increased microbial activity and decomposition (Bowden et al. 1998; Conant et al. 2011). Therefore, sites in colder regions may be more sensitive to changes in temperature than those in warmer climates as those are already in more optimal temperature ranges (i.e., lower response). With respect to WT, model results show that WT sensitivity was correlated with the initial WT depth. Sites with high water tables were the most sensitive to changes in temperature and precipitation, and those with deep water tables were the least sensitive. Previous riparian studies have shown that sites with shallow confining layers and smaller upland aquifers experience enhanced seasonal variability in groundwater inputs/WT depth (i.e., increase sensitivity to weather changes) compared to those connected to large upland aquifers (Vidon and Hill 2004c). In our model, sites with deep water tables correspond to sites with deep confining layers, and therefore sites likely connected to large upland aquifers. Our model is therefore consistent with our understanding of the impact of deep confining layer and/or large upland aquifer on sensitivity to climate change. However, when it comes to PO_4^{3-} dynamics, results remain unclear. In this analysis, sites at the extremes of very low or very high PO_4^{3-} concentration values were estimated to be the least sensitive to changes in temperature. In other words, based on RZ-TRADEOFF outputs, sites with very deep confining layer depth (15 m) or with warmer temperatures (Mid-Atlantic region) may tend to have low sensitivity with regard to PO_4^{3-} concentration. In turn, sites with mid-range values for PO_4^{3-} concentrations should show the greatest change in response to weather perturbations based on model outputs. Kaushal et al. (2008) noted that the impact of temperature variability on PO_4^{3-} dynamics is still unclear, and more field observations are certainly warranted to validate these findings as few studies have assessed the impact of temperature on PO_4^{3-} concentrations.

What are the similarities, trade-offs, and correlations in riparian functions as predicted by RZ-TRADEOFF?

Cluster analysis suggests that when all functions are considered, modeled riparian sites in the Mid-Atlantic were more similar to each other than sites from other regions, likely due to the temperature being much warmer in the Mid-Atlantic region than in the other regions, which in turn strongly influences PO_4^{3-} concentration at the field edge and CO_2 emissions (Table 3). On a regional basis, cluster analysis therefore suggests that temperature may have more influence on overall site variability (i.e., all variables considered together) than site geomorphic characteristics or land use. While climate has been shown to have limited impact on riparian functions such as NO_3^- removal (Sabater et al. 2003), this clustering highlights the strong influence of temperature on CO_2 emissions (Bowden et al. 1998; Harper et al. 2005; Morse et al. 2012). The results of the cluster analysis also showed that sites with high NO_3^- removal (100%) or/and high NO_3^- concentration at the field edge formed one cluster. This suggests that sites with characteristics that lead to high NO_3^- concentration may often also have high N removal, which is consistent with studies showing NO_3^- load as being positively correlated with NO_3^- removal (Sabater et al. 2003; Vidon and Hill 2004b).

Beyond cluster analysis, factor analysis highlighted that sites with deep mean WT depths will generally be associated with high PO_4^{3-} concentrations at the field edge as well as higher N_2O emissions (Table 4). Conversely, riparian zones with shallow confining layers and shallow WT depths can be expected to have low PO_4^{3-} field edge concentrations and low N_2O fluxes. Another factor of importance revealed by the factor analysis is that sites with high NO_3^- concentration at the field edge also have high NO_3^- removal. This is consistent with the results from the cluster analysis (see "Discussion" above). Therefore, while riparian zones in agricultural areas can be expected to have high NO_3^- inputs, they are also expected to remove a high percentage of the incoming NO_3^- and act as a strong sink. Meanwhile, riparian sites in low density residential and forested areas may have lower efficiency and remove a smaller percentage of NO_3^-, though the initial inputs will likely be lower than those in agricultural areas (Table 5).

Another important finding from this study in terms of trade-off is that temperature strongly influences riparian CO_2 and CO_2 equivalent fluxes, suggesting that riparian zones in warmer climate might have a higher impact on overall GHG than those on colder climate, all other parameters being equal (Table 5). Although technically correct, this argument needs to be balanced by the fact that GHG emissions from riparian soils would occur, regardless of management (e.g., if the riparian zone was in agriculture). Although GHG are higher in warmer

Table 5 Summary table illustrating the influence of geomorphic characteristics, weather, and land use/land cover on riparian functions based on analysis of RZ-TRADEOFF model outputs and calculations. Legend: CH_4, methane emissions at the soil-atmosphere interface; CO_2, carbon dioxide emissions at the soil-atmosphere interface; NO^{3-} removal, percent nitrate removal in subsurface flow; NO^{3-}, nitrate concentration at the field edge; N_2O, nitrous oxide emissions at the soil-atmosphere interface, PO_4^{3-}, phosphate concentration at the field edge; PO_4^{3-} removal, phosphate removal in subsurface flow; TP, total phosphorus removal in overland flow; WT, water table depth below ground surface

Riparian function	Influence of riparian characteristics
WT depth below ground surface	Generally dependent on confining layer depth and weather/precipitation. Deeper confining layer depth increases the mean depth to water table. Warmer temperatures and/or lower precipitation are also expected to increase depth to water table.
Ground water flux	Calculations sensitive to hydraulic conductivity. Very high calculated flux values possible for sites with coarse soils (sandy loam, sand, coarse sand, and gravel) and high hydraulic conductivity.
NO_3^- concentration at the field edge	High concentration when slope at the field edge is steep (10% or greater) and low concentration when slope at field edge is flat. Fertilized cropland in the immediate upland area also increases NO_3^- concentration compared to residential or forested upland land cover.
NO_3^- removal in subsurface flow	Percent removal greater than 40% only in areas with fertilized cropland in the immediate upland area.
Mass of N removed	Strong sinks generally associated with site with high NO_3^- concentration at the field edge. Sites with fertilized cropland in the upland and steep slopes generally have a higher sink strength. Some sites, without these characteristics, can still produce sink strengths greater than 1 (g N m^{-1} day^{-1}), especially if soil type is coarse (i.e., sand, coarse sand gravel, sandy loam) and hydraulic conductivity is high.
PO_4^{3-} concentration at the field edge	Concentration increases with increasing confining layer depth. Warm climate regions (i.e., Mid-Atlantic) have lower concentrations than those in comparatively colder regions (i.e., Northeast, New England).
TP removal in overland flow	Dependent on buffer width. Very high removal (approx. 90%) for all sites 10 m or wider. Narrow buffers (5 m or less) result in substantially lower removal (< 70%).
PO_4^{3-} removal in subsurface flow	Constant 1.5%.
N_2O emissions at the soil-atmosphere interface	Dependent on confining layer depth in the upland. Greater depths increase N_2O flux to the atmosphere.
CH_4 emissions at the soil-atmosphere interface	Riparian zones with all mineral soil types act as CH_4 sinks overall. Peat sites are a strong source of CH_4 (constant 621.5 mg m^{-2} day^{-1}).
CO_2 emissions at the soil-atmosphere interface	Emissions positively correlated with temperature. Warm temperatures (i.e., Mid-Atlantic region) substantially increase CO_2 flux to the atmosphere.
CO_2 equivalent emissions at the soil-atmosphere interface	Riparian zones with higher CO_2 flux (warmer temperatures) will generally have higher CO_2 equivalent fluxes as well. The presence of peat results in the highest CO_2 equivalents regardless of temperature due to the high contribution of CH_4.

climate at mid-latitudes, further research is needed to established background (i.e., without riparian zones) soil emission to make specific recommendations about the impact of riparian zones on GHG emissions on a regional basis. Another trade-off also exists with regard to buffer width and TP removal in overland flow (Table 5). Narrow buffers (< 10 m) may be useful if space is limited, as they still can potentially act as nitrate sinks and have a smaller GHG impact. However, narrow buffers have the trade-off of reduced TP removal capacity in overland flow, and therefore may not be ideal for areas where P management is a priority.

Management applications and conclusions

From a management standpoint, the analysis of RZ-TRADEOFF outputs provides a useful guide to generalize water and air quality functions at the watershed scale. In this context, we recommend for each user to identify the characteristics (weather/climate, land use/land cover, geomorphology) of the site(s) they are trying to manage and compare them to Supplementary Table S1 to determine the best match or matches to our modeled sites. Next, the user can visit Supplementary Table S2, showing the individual model output for each modeled site to start understanding the most likely behavior of the site or sites they are trying to manage. Indeed, our review of model outputs for the representative sites in relation to the literature and our current understanding of riparian hydrology and biogeochemistry indicates that overall, the model output matched relatively well with field data from published studies. RZ-TRADEOFF outputs for management are therefore a reasonable approach to provide management suggestions. However, running the model for individual sites will be useful in cases where more tailored, site-specific estimates are needed/desired. Additionally, since one weather station per region was used for our analysis, running the model with temperature and precipitation data more specific to an area of interest may result in somewhat different estimates for the weather-dependent variables than what was calculated for our modeled sites.

An important take home message from this study is that there is not one set of climate, hydrogeomorphic, or land use/land cover conditions that is ideal (or bad) for all variables related to riparian functions. As highlighted in this analysis, there are multiple possible combinations of site characteristics that have varying influence on riparian functions. Ultimately, we believe that RZ-TRADEOFF and the wide array of synthetic sites (80) tested here constitute a solid platform for management decisions in a multi-contaminant context, and that research results presented here significantly contribute to a better understanding of how to optimize riparian restoration and protection in watersheds based on both water (nitrogen, phosphorus) and air quality (GHG) goals.

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