Journal of Hydrology 522 (2015) 123–134

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Using a soil topographic index to distribute denitrification fluxes across a northeastern headwater catchment

Todd R. Anderson [a,1], Peter M. Groffman [b], M.Todd Walter [a,*]

[a] Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, United States
[b] Cary Institute of Ecosystem Studies, P.O. Box AB, 2801 Sharon Turnpike, Millbrook, NY 12545, United States

ARTICLE INFO

Article history:
Received 6 June 2014
Received in revised form 13 November 2014
Accepted 18 December 2014
Available online 27 December 2014
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Pedro J. Depetris, Associate Editor

Keywords:
Denitrification
Hotspots
Scaling measurements
Riparian zone
Saturated zone

SUMMARY

Riparian zones are considered potential hotspots of denitrification because they allow for the confluence of necessary electron acceptors (nitrate) and donors (carbon) via hydrologic flowpaths in low oxygen (reducing) conditions. While riparian areas have received considerable research attention, other soils prone to saturation have similar physicochemical characteristics but are less frequently studied. We quantified *in situ* denitrification rates in the shallow saturated zone, a dynamic portion of the landscape, across a range of hydroperiodicities, i.e., frequencies and durations of saturated conditions, as characterized by a topographic index in a small mixed land-use headwater catchment in central New York State. We found a strong positive relationship between topographic index and denitrification, indicating that the highest rates of denitrification occur in the relatively small portion of the landscape prone to saturation. We used the resulting relationship to distribute denitrification rates across the catchment and estimate denitrification fluxes from the shallow saturated zone. While the highest rates of denitrification were observed in wetter portions of the landscape, including riparian zones, we found that the shallow saturated zone beneath drier upland soils contributed to a larger portion of whole-catchment denitrification due to a larger areal extent. A topographic index-denitrification model is a promising and simple tool that allows for scaling of *in situ* denitrification rates across the landscape and provides insight into the spatial organization of denitrification at the catchment scale.

1. Introduction

Denitrification is an important part of the nitrogen (N) biogeochemical cycle and a valuable ecosystem service for protecting aquatic habitats from nonpoint source pollution. Unfortunately, it is also difficult to measure in the environment. It is commonly estimated at landscape or watershed scales as the difference between all the measurable N-inputs and -outputs (e.g., van Breemen et al., 2002; Gentry et al., 2009). While this type of large-scale mass balance approach is powerful, it is difficult to meaningfully attribute denitrification rates across a heterogeneous landscape. In fact, it is widely recognized that there are biogeochemical hotspots, which account for small fractions of the landscape but show disproportionately high rates relative to the surrounding area (McClain et al., 2003). Denitrification rates are especially high in carbon (C)-rich parts of the landscape with low oxygen (O_2) levels and sufficiently high nitrate (NO_3^-) concentrations (e.g., Hill et al., 2000; Burgin et al., 2010). These conditions are commonly associated with riparian areas, wetlands, and other parts of the landscape prone to wet or saturated soil conditions. Because these types of areas are recognized as likely denitrification hotspots, many studies have focused on measuring denitrification from these spots. However, it is difficult to translate these point measurements to landscape or watershed scales. Finding ways to quantify denitrification across scales may help environmental planners develop better strategies for targeting management practices for reducing nonpoint source N pollution in streams, lakes, and coastal ecosystems (Walter et al., 2007).

Because denitrification hotspots are commonly associated with wet soils, several researchers have suggested that there is good potential for capturing hotspot activity by coupling hydrological and denitrification processes (e.g., Vidon and Hill, 2004; Burt and Pinay, 2005; Tague, 2009). Parallel to the biogeochemical hotspot concept, the variable source area (VSA) concept in hydrology describes how storm flow in many humid areas is largely generated on the small parts of the watershed that are especially prone to becoming saturated (e.g., Hewlett and Hibbert, 1967; Dunne and

---

* Corresponding author. Tel.: +1 607 255 2488.
E-mail address: mtw5@cornell.edu (M. Walter).

[1] Current address: Department of Environmental Studies, Mount Holyoke College, South Hadley, MA 01075, United States.

http://dx.doi.org/10.1016/j.jhydrol.2014.12.043
0022-1694/© 2015 Elsevier B.V. All rights reserved.

Black, 1970a, 1970b) or at least wet enough to allow rapid lateral flows (e.g., Anderson and Burt, 1978; Lyon et al., 2006b). In the northeastern US, regional hydrology is largely characterized by VSA processes (e.g., Walter et al., 2000). The soils are generally very permeable relative to typical rainfall rates (Walter et al., 2003). Thus, most rainfall infiltrates and is redistributed by gravity-driven subsurface flow. While the resulting patterns of soil moisture are highly heterogeneous in space and time, they are relatively predictable with VSA concept hydrological models (e.g., Holko and Lepisto, 1997; Mehta et al., 2004). These hydrological models may thus be a useful tool for accurately modeling the occurrence of biogeochemical hotspots (Richardson et al., 2007).

The soil topographic index (STI) (e.g., Walter et al., 2002; Lyon et al., 2004; Agnew et al., 2006), a reconceptualization of the topographic index (TI) developed by Beven and Kirkby (1979), incorporates many of the landscape-scale features indicative of primary denitrification controls, specifically (1) upland drainage-area size; (2) depth and permeability of saturated sediments; and (3) topographic slope (Vidon and Hill, 2004):

$$\mathrm{STI} = \ln\left(\frac{a}{\tan(\beta)K_{sat}D}\right) \quad (1)$$

where a is upslope contributing area per unit contour length (m), $\tan(\beta)$ is the local surface topographic slope, K_{sat} is the mean saturated hydraulic conductivity of the soil ($\mathrm{m\,d^{-1}}$), and D is the soil depth (m). According to the TI concept, soil moisture and groundwater level of a location are a result of the upslope contributing area and drainage (expressed as a slope). The TI (also referred to as "topographic wetness index") is considered an index of hydrological similarity: the higher the index value, the wetter the point and the more frequently a point will be saturated to a given level, relative to other points in the same landscape (Ambroise et al., 1996). TI has been shown to be a good predictor of soil moisture content or shallow groundwater level (e.g., Burt and Butcher, 1985; Moore et al., 1993; Western et al., 1999; Lyon et al., 2006a, 2006b; Sorensen et al., 2006; Schneiderman et al., 2007; Buchanan et al., 2014) and has been used to quantify hydroperiodicity, i.e., frequencies and durations of saturated conditions (e.g., Agnew et al., 2006). Furthermore, several studies have indicated additional relations between TI and other physiochemical properties of soil (or its porewater) that are known to influence denitrification, including soil organic matter (OM) and C, soil N, dissolved organic carbon (DOC), $\mathrm{NO_3^-}$, pH, soil texture, and bulk density (e.g., Moore et al., 1993; Florinsky et al., 2004; Ogawa et al., 2006; Seibert et al., 2007). We should note that the TI concept applies best to humid areas with distinctly sloping landscapes and some formulations of the TI work better than others; See review and analyses by Buchanan et al. (2014).

Despite the connection between TI and soil moisture, and research indicating that topographic control of soil moisture may promote denitrification (e.g., Pennock et al., 1992; Van Kessel et al., 1993), we found only one study that has evaluated the TI-denitrification relation (Florinsky et al., 2004). This is likely because it is only with the maturation of geographic information systems (GIS) and readily available, high resolution digital elevation model (DEM) data that we have had the easy ability to generate TI maps at resolutions of interest. Florinsky et al. (2004) studied the effect of topography on the activity of denitrifiers under different soil moisture conditions in an agroecosystem and found that denitrification rates generally increase with increasing TI under wet conditions, but not drier conditions. Their interpretation was that some threshold amount of water was required to maintain topographic control on the spatial distribution of denitrifier activity. In other words, when it is wet (above some threshold), gravity-driven transport of nutrients coupled with anaerobic conditions promote denitrification in higher TI areas; conversely, when it is dry, one or both of those components are likely missing and denitrification is low in most parts of the landscape. However, their study considered one wet period and one dry period, both lasting a single month. Agnew et al. (2006) demonstrated a clear, regionally consistent relationship between STI and probability of saturation with strong correlation throughout the year [probability of saturation was the sum of all days over a 30-year period that a point in a watershed was saturated divided by the total days simulated – the specific relationship shifted from month to month]. Combined, these two studies suggest that TI and denitrification should show a positive correlation on an annual basis, and the resulting relationship may be a useful tool to model or predict the spatial distribution of denitrification at landscape or watershed scales. Note, day-to-day relationships between TI and soil moisture status or denitrification will likely vary substantially, so here we are considering annual averages.

The goal of the study was to determine if annual denitrification rates correlated with STI within the catchment, and if so, use that relationship to distribute rates (as fluxes) across a watershed to estimate whole-catchment denitrification occurring in the shallow saturated zone. Thus, the specific objectives were to: (1) quantify *in situ* denitrification across a range of hydroperiodicities as characterized by the STI in a small mixed land-use headwater catchment in central New York State; and (2) estimate shallow groundwater denitrification at the catchment-scale using a simple STI-denitrification regression model. We measured denitrification rates using the $^{15}\mathrm{N{-}NO^3}$ push–pull method at monthly intervals across a range of STI over a one-year period. We also characterized physiochemical variables known to influence rates of denitrification and related those to STI. This is a critical area for denitrification, but there has been no analysis of its variation in this zone and its link to surface topography.

2. Methods

2.1. Study area description

We measured *in situ* denitrification rates across gradients of hydroperiodicity, as defined by STI, in a small headwater catchment near Harford, NY, USA (Fig. 1). The catchment is a sub-basin of the Owego-Wappasening Watershed which drains into the Susquehanna River near the NY–PA state border. The catchment is 1561 ha (15.6 km^2), with elevation ranging from 360 m at the outlet to 614 m along the valley ridgetops. Records (2005–2011) from a recently deployed NOAA U.S. Climate Reference Network monitoring station on site (NY Ithaca 13E, 42.44°N, 76.25°W, 374 m elevation) indicate an annual mean temperature of 7.4 °C with monthly mean temperatures ranging from −5.3 °C in February to 19.4 °C in July (http://www.ncdc.noaa.gov/). Mean annual precipitation is 1076 mm yr^{-1} with more precipitation on average in summer (114 mm mo^{-1}) than winter (75 mm mo^{-1}). Snowfall averages 1583 mm yr^{-1}. The year of this study, 2008, was, on average, typical with 7% less precipitation, 4% more snow, and about 1% warmer than the climatic averages. Land cover in the catchment is predominantly agricultural (44%) and forested (41%) with the rest in shrub/grassland (8%), wetlands (4%), or developed (3%) according to the 2006 NLCD (Fry et al., 2011; http://www.mrlc.gov/). Additional descriptions of the study watershed can be found in Supplemental material and Anderson (2013).

2.2. Site characterization and instrumentation

Three sites in the catchment were chosen to investigate the relation between *in situ* denitrification and the propensity of saturation. In order of decreasing elevation, these sites in the landscape