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Assessing denitrification from seasonally saturated soils in an agricultural landscape: A farm-scale mass-balance approach

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ABSTRACT

Riparian zones have received considerable attention as potential hotspots of denitrification at the landscape- or watershed-scale. Conceptually, the conditions that promote denitrification in these zones are also found in other parts of the landscape, namely those areas that are prone to saturate. However, spatiotemporal characterization and quantification of these potential denitrification hotspots are lacking, despite their importance to land managers tasked with mitigation of nitrogen (N) pollution, particularly in human-dominated landscapes. We quantified denitrification fluxes from the shallow saturated zone of an agricultural landscape using a topographic index-denitrification model, which facilitates scaling of in situ denitrification rates across the landscape based on frequency and duration of saturated conditions. Denitrification in the shallow saturated zone (i.e., where the water table is at or within a few meters of the soil surface) resulted in a N flux that was nearly half of the total denitrification from the landscape—in about a third of the area—as determined from a well-constrained whole-farm N balance constructed from farm records and field measures. Denitrification flux rates from saturated riparian soils were among the highest in the landscape, however the contribution of riparian areas to total landscape denitrification was less than 10%.

1. Introduction

The issue of nitrogen (N) pollution and the dominant role of agriculture as a major nonpoint source of N pollution is well recognized (e.g., Galloway et al., 2003; Robertson and Vitousek, 2009; Smil, 1999). Agricultural production results in unavoidable losses of reactive N to the environment via multiple pathways, such as leaching of nitrate (NO_3^-) to surface and groundwater, volatilization of ammonia (NH_3) from soils, and fluxes of nitrous oxide (N_2O) and other reactive N-containing gases (NO_x) to the atmosphere. Environmental consequences of these reactive N forms include eutrophication of coastal zones, compromised air and water quality, climate warming, and biodiversity changes in receiving ecosystems (Davidson et al., 2012). Successful management of N in agroecosystems attempts to maximize crop and/or animal production while minimizing environmental loss of N (referred to as nitrogen use efficiency, or NUE). This task is complicated by multiple transformation processes within the N cycle (e.g., mineralization, immobilization, volatilization, fixation, nitrification, denitrification) (Galloway et al., 2003). Denitrification, the microbial transformation of NO_3^- to N gases, is of particular interest and important in agricultural landscapes because it is capable of reducing a reactive form of N (NO_3–N) to a non-reactive form (inert N_2) (Seitzinger et al., 2006).

Denitrification is a facultative anaerobic process utilized by specific groups of heterotrophic microbes that are ubiquitous in terrestrial soils; oxygen (O_2) and available carbon (C) and nitrate (NO_3^-) are widely regarded as the main factors controlling denitrification activity at the organism scale (Firestone, 1982; Knowles, 1982). However, estimating denitrification fluxes at larger scales (e.g., landscape or watershed) is problematic due to high spatial and temporal variability of the environmental regulators of O_2, C, and NO_3^-, giving rise to hotspots and hot moments of denitrification (Groffman et al., 2009; McClain et al., 2003). Denitrification hotspots can be biogeochemically process-driven and/or transport-driven; the former due to locally anoxic conditions and the presence of labile C, the latter due to solute fluxes in water (Vidon et al., 2010).

Riparian zones have received considerable attention as potential hotspots of denitrification because they allow for the confluence of necessary electron acceptors (NO_3^-) and donors (C) via hydrologic

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flowpaths in low O_2 (reducing) conditions (e.g., Hedin et al., 1998; Vidon and Hill, 2004a). However, these conditions exist along a continuum throughout the landscape, and include areas prone to saturate both permanently and periodically (e.g., Hill, 2000; Walter et al., 2000). Indeed, groundwater fluctuations and their control on anaerobic conditions and nutrient fluxes have been shown to promote denitrification in riparian buffers, wetlands, and other areas experiencing saturation (e.g., Hefting et al., 2004; Reddy and Patrick, 1975; Woli et al., 2010). Similarly, increased hydrological connectivity via shallow groundwater is thought to enhance NO_3^- removal though denitrification (e.g., Kaushal et al., 2008; Roley et al., 2012; Vidon and Hill, 2004b,c).

Despite the emerging importance of denitrification hotspots, there remains a critical knowledge gap: how much of the denitrification in a landscape or watershed can be attributed to these hotspots? Spatiotemporal distribution of these denitrifying zones have not been characterized. This is partially due to the fact that, until recently, techniques for measuring denitrification in situ at specific points in the landscape were not well developed (Groffman et al., 2006). And only recently—with the continued development of geographic information systems (GIS)—have we had the ability to model hydrologic processes in a fully distributed manner. Scaling-up site specific measurements to ecosystem or larger scales has been identified as a critical need for denitrification research (Boyer et al., 2006; NSF (National Science Foundation), 2012).

In a companion study, we quantified in situ denitrification rates across a range of hydroperiodicities, i.e., frequencies and durations of saturated conditions, as characterized by a topographic index (TI) in a small, agricultural headwater catchment (manuscript submitted). TI (also referred as 'topographic wetness index') is considered an index of hydrological similarity: the higher the index value, the wetter the point in the landscape and the more frequently the point will be saturated relative to other points in the same landscape (Ambroise et al., 1996). The soil topographic index (STI) (e.g., Agnew et al., 2006; Walter et al., 2002), a slight variation of the 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, 2004c):

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

where a is upslope contributing area per unit contour length (m), tan (β) is the local surface topographic slope, K_{sat} is the mean saturated hydraulic conductivity of the soil (m d^{-1}), and D is the soil depth (m). We found a strong positive relationship between STI and denitrification, as well as significant relationships between STI and dissolved oxygen in shallow groundwater, dissolved organic carbon, and physicochemical soil properties known to increase denitrification potential. We used the resulting STI–denitrification relationship to distribute denitrification rates across the catchment and estimate denitrification fluxes from the shallow saturated zone. We compared rates/fluxes to other published values in similar settings, and concluded that a large portion of whole-catchment denitrification was occurring in the shallow saturated zone, and that these areas should be conceptualized as hotspots of potential denitrification activity. However, our analysis did not evaluate denitrification fluxes in context of other major components of the N cycle or the total N budget for the watershed.

Nitrogen budgets or balances are useful tools for expanding our understanding of the N cycle at any scale of interest. In agroecosystems, N budgets are typically used to document the major N flow paths, sources, and sinks as a way to develop estimates of N use efficiencies, evaluate N management strategies, and/or identify areas of environmental N loss (Meisinger et al., 2008; Meisinger and Randall, 1991; Mosier et al., 2004). Each N balance is unique: tailored to a specific set of goals and requiring a clear definition of spatial and temporal boundaries which ultimately determines the N flow paths and sources/sinks to be considered. Conservation of mass is the principle on which N balances are based:

$$\mathrm{N_{inputs}} = \mathrm{N_{outputs}} + \Delta\mathrm{N_{storage}} \tag{2}$$

where the mass of N entering is equal to the mass of N leaving plus the change of N stored in the system, over a given time period. Major N inputs into agroecosystems may include atmospheric deposition, inorganic fertilizers, animal manure, biological fixation, and feed imports; major N outputs may include harvested crops, animal products, volatilization losses from manure or fertilizer, denitrification, leaching losses, and surface runoff. A quasi steady-state condition is often assumed to simplify agricultural N balances, so the ΔN term is taken to be zero. This condition implies that soil N mineralized from soil on an annual basis is balanced by N immobilized (e.g., in residues and roots or as new soil microbial biomass). Consistent application of the same N management practices over many years is key to attaining a quasi steady-state condition; other factors include climate and weather, soil properties, tillage, N additions, and cropping system (Meisinger et al., 2008). Nitrogen balances, as described above, have been used to make estimates of landscape- or watershed-scale denitrification. In this method, all the N inputs and N outputs—other than denitrification—are estimated or measured, and the resulting N surplus is assumed to be balanced by denitrification (e.g., Gentry et al., 2009; Puckett et al., 1999; van Breemen et al., 2002).

Our goal in this study was to quantify denitrification occurring in shallow saturated zone hotspots of an agricultural landscape, and compare it to total denitrification and other N fluxes in the same landscape to investigate the contribution and relative importance of these hotspots to the mitigation of nonpoint source N pollution. We used the methodology developed in and results from our companion study (manuscript submitted) to estimate the denitrification flux from the shallow saturated zone of an intensive dairy farm under a corn/alfalfa production system. A whole-farm N balance was constructed from detailed farm records and direct measurements to estimate the remaining N sources and sinks, including total denitrification (via the difference method).

2. Materials and methods

2.1. Description of study area

The study was carried out at the Cornell University Animal Science Teaching and Research Center (T&R Center) located near Harford, NY, USA (Fig. 1). The T&R Center occupies 1052 ha of land, of which 159 ha was in pasture and 456 ha was cropped corn or alfalfa in rotation to support intensive dairy production. The remaining acreage is utilized by dairy, beef, and sheep unit facilities. Daily average herd size during the study was 1050 dairy cattle, 195 beef cattle, and 1100 sheep. All manure is stored on site and surface spread without incorporation into the soil, often on a daily basis. Animal products sold include milk and wool, plus live animals to adjust herd size and composition. NPK fertilizers are used during the planting of corn as a starter and later as a sidedress depending on rotation (e.g., corn not following alfalfa) and/or results of pre-sidedress nitrogen tests. Harvested crops, primarily corn silage and alfalfa hay silage, stay on the farm and are used to supplement imported feed. Alfalfa is harvested in three cuts during the summer and fall; corn is harvested once in the fall. Reduced tillage practices follow harvest and precede most seeding operations (T. Eddy, T&R Center Director of Operations, personal communication).