Ecological Engineering 85 (2015) 67–75

Contents lists available at ScienceDirect

Ecological Engineering

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

Hydrologic conditions drive denitrification and greenhouse gas emissions in stormwater detention basins

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ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form
30 September 2015
Accepted 7 October 2015

Keywords:
Greenhouse gases
Denitrification
Methane
Nitrous oxide
Stormwater
Urban systems

ABSTRACT

Stormwater detention basins are primarily designed to detain large volumes of storm runoff and trap suspended sediments and associated pollutants. Detaining and retaining nutrients are often not a design focus. The combination of variable moisture patterns in stormwater basins along with potential nutrient influxes may make these basins hotspots for nitrogen transformations such as denitrification, as well as potential sources of greenhouse gases nitrous oxide (N_2O) and methane (CH_4). Nitrous oxide and CH_4 emissions were measured using static chambers in four stormwater detention basins – two fast-draining or 'dry' basins and two slow-draining or 'wet' basins. Denitrification potential of soils collected from these basins was also measured using the denitrification enzyme assay (DEA). While N_2O emissions were low, CH_4 emissions were higher in both wet basins, averaging 5667 $\mu g\,C\,m^{-2}\,h^{-1}$ in the wettest basin. Denitrification potential was higher in the wet basins (2.27 $mg\,N\,kg^{-1}\,h^{-1}$) compared to the dry basins (0.23 $mg\,N\,kg^{-1}\,h^{-1}$). Overall, wet detention basins had higher greenhouse gas emissions but also had higher potential for nitrate removal via denitrification. Designing future stormwater control measures to maintain a subsurface saturated zone rather than fully saturated soils should be considered to promote denitrification while also reducing CH_4 emissions at the surface.

1. Introduction

As land is urbanized, stormwater control measures (SCMs) are implemented to deal with runoff generated on impervious surfaces. These SCMs include structures such as detention ponds and basins and are intended to temporarily detain stormwater in order to reduce peak streamflows and nuisance flooding. As management of pollutants in urban runoff became a concern, SCMs have taken on an additional role as water quality best management practices. In the United States, SCMs are a key strategy supported by the U.S. Environmental Protection Agency (EPA) for managing stormwater in urbanized areas and satisfying Clean Water Act water quality goals (US EPA, 2014). The primary water quality target for SCMs has generally been sediment and associated pollutants such as heavy metals (Davis and McCuen, 2005). Metals and hydrocarbons are prevalent in urban runoff due to vehicle exhaust and weathering of vehicle and building components (Brown and Peake, 2006; Davis et al., 2001).

Nitrogen can also be a concern in urban areas due to sources such as atmospheric deposition on impervious surfaces (Bettez and Groffman, 2013), leakage of septic and sanitary sewer systems, lawn fertilizers and pet waste (Kaushal et al., 2006). However, nutrients, which are often in dissolved form and not readily treated through filtration or sorption, are generally not the primary focus of SCM design (Collins et al., 2010). More recently, there has been some consideration of how to optimize nitrogen removal in these systems using a subsurface saturated zone and/or carbon amendments (Hunt et al., 2012; Kim et al., 2003). Both of these promote denitrification, the microbially-mediated transformation of nitrate (NO_3^-) to nitrogen gases (Seitzinger et al., 2006). Older SCMs, which were not designed explicitly for nitrogen removal, may still facilitate conditions that promote denitrification. Studies of SCMs in Baltimore, Maryland and Phoenix, Arizona found that these structures had higher denitrification potential than stream riparian areas, which are typically viewed as 'biogeochemical hotspots' for the transformation of inorganic nitrogen to gaseous nitrogen (Bettez and Groffman, 2012; Zhu et al., 2004).

Just as these SCMs can be hotspots for denitrification, they may also be hotspots for production of greenhouse gases (GHGs), namely nitrous oxide (N_2O) and methane (CH_4). N_2O has 298

Abbreviations: GHG, greenhouse gas; NO_x, $NO_3^- + NO_2^-$; LOI, loss-on-ignition; OM, organic matter; SCM, stormwater control measure; VWC, volumetric water content.

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http://dx.doi.org/10.1016/j.ecoleng.2015.10.018
0925-8574/

times the warming potential of carbon dioxide (CO_2) (Solomon et al., 2007) and can be produced by denitrification as well as by nitrification, as an intermediary in the conversion of ammonia to nitrate (Firestone and Davidson, 1989). CH_4 has 25 times the warming potential of CO_2 (Solomon et al., 2007) and is produced by methanogenesis in the anaerobic respiration of organic molecules or reduction of CO_2 (Schlesinger, 1997). Production of either gas requires carbon substrate, which could be provided by the basin soil media or by particulate organic matter (OM) or degradation products of hydrocarbons in incoming runoff. These processes are also strongly controlled by oxygen status in the soil. Denitrification and methanogenesis are both promoted under anaerobic conditions, while variation between anaerobic and aerobic conditions can promote cycling between nitrification and denitrification and subsequent N_2O production (Burgin and Groffman, 2012; Christiansen et al., 2012). Thus, variation in soil moisture or existence of saturated zones in the SCM could influence these processes and associated GHGs. The only published data on GHG dynamics in SCMs thus far has been for bioretention cells in Melbourne, Australia (Grover et al., 2013). Bioretention systems expand on the typical wet or dry detention basin to include an infiltration zone and plants to stimulate soil microbial activity to provide overall better pollutant removal. The researchers found the cells to be slight sources of N_2O and sinks of CH_4 under most conditions, but observed pulses of both gases after simulated rain events (Grover et al., 2013).

As peri-urban land use expands (Brown et al., 2005) and more SCMs are built to mitigate ensuing hydrologic alterations, it is important to understand the impact of these structures on landscape biogeochemical processes. The ability of these structures to act as hotspots of nutrient retention or as sources of greenhouse gases could have a substantial impact when scaled up, and should be considered along with other ecosystem services provided by green stormwater infrastructure. However, data on these processes in various parts of urban ecosystems is still lacking (Pataki et al., 2011).

1.1. Objectives/Hypotheses

The objective of this study was to survey greenhouse gas emissions (N_2O and CH_4) and denitrification potential across four traditional stormwater detention basins in a northern temperate climate, and identify drivers of observed patterns. We hypothesized that rates of these processes would be higher within the basins than in adjacent lawns, due to the influx of nutrients and variability in soil wetness resulting from periodic storm runoff. We also hypothesized that the hydrologic regimes of the basins would be a major control on differences in these biogeochemical processes across basins, with wetter basins exhibiting greater denitrification and CH_4 emissions and drier basins having higher N_2O emissions due to contributions from both denitrification and nitrification.

2. Methods

2.1. Study site

The four stormwater basins (Fig. 1a) were located on the Cornell University campus in Ithaca, New York, USA. This region is characterized by a temperate climate, with an average annual temperature of 8.1 °C, average range of −9.2 to 26.6 °C and average annual precipitation of 947 mm (NRCC, 2014). All basins were constructed between 2002 and 2007 and vary between 400 and 1410 m^2 in size, though the ratio of their watershed drainage areas compared to basin area were similar (Table 1). Designed as dry detention basins, they were planted with turfgrass (primarily *Lolium perenne*) and have 10–15 cm topsoil which is underlain by native silt loam, and then a layer of sand. Below the sand is an underdrain (perforated pipe) that connects to the storm sewer system and is intended to route water away during periods of saturation. All basins were intended to drain within approximately 24 h of filling. Since construction, drainage in two of the basins has slowed, leading to wetter soils in these basins (Fig. 2) and the emergence of vegetation common in local wetlands (e.g. *Juncus* sp., *Typha* sp.). Reasons for the change are uncertain, but may include reduced infiltration due to settling of fine particles (Paus et al., 2014), aggregate formation and pore clogging due to reactions with road salt (Kakuturu and Clark, 2015) or clogging of the underdrain.

Soil and gas measurements were made at three locations within each basin and two reference locations directly outside of each basin (Fig. 1b). The outside locations provided references where the soil media was the same as within the basin itself (verified through textural analysis described below), but which did not receive the same inputs of stormwater and nutrients as the basin.

2.2. Gas flux measurements

Emissions of CH_4 and N_2O were measured at the basins on seven dates between March and November 2013 that provided a range of temperature and moisture conditions. Average air temperature for the seven dates ranged from 1.7 to 18.9 °C and precipitation in the three preceding days for each measurement date ranged from 0 to 1.8 cm (NRCC, 2014). Flux measurements at the four basins occurred within 3 h of each other on the same day for each time-point. Fluxes were measured using in situ static chambers which were 30 cm in diameter and constructed using two plastic buckets. The chamber base was created by cutting a five gallon bucket in half such that the ribbed top of the bucket could be installed in the soil. These bases remained in place for the entire duration of the study. Two 1.5 cm holes were drilled in each chamber base to allow for flow of water during storm events. In preparation for making a gas flux measurement, a 5 cm wide rubber band was placed around the chamber base and the two holes in the chamber base were plugged with rubber stoppers. The chamber top was constructed from a 3.5 gallon bucket equipped with a rubber septum for sampling and a vent tube. Additional chamber construction details are described in Molodovskaya et al. (2011).

For a single gas flux measurement, the chamber top was mounted on the base and a 20 mL syringe was inserted into the main septum to take an initial gas sample. Samples were injected into pre-evacuated 10 mL glass vials with butyl rubber septa. Vials were over-pressurized with injection of 15 mL gas in order to maintain the integrity of samples until analysis. Additional gas samples were taken from the chamber at 10, 20, and 30 min.

Samples were analyzed for N_2O and CH_4 using an Agilent 6890 N gas chromatograph equipped with a HP 7694 Headspace Autosampler (Hewlett-Packard Co.). N_2O separation was performed using a Supel-Q™ PLOT capillary column (30 m × 0.32 mm; Supelco Inc.) with ultra-pure helium carrier gas (2.6 mL min^{-1}) and 95:5 Ar:CH_4 make-up gas (8.2 mL min^{-1}) and a μECD (electron capture detector) set to 250 °C. CH_4 separation was performed using a Carboxen 1006 PLOT capillary column (30 m × 0.32 mm; Supelco, Inc.) and an FID (flame ionization detector) set to 200 °C with H_2 gas (30 mL min^{-1}), air (400 mL min^{-1}), and N_2 makeup gas (25 mL min^{-1}). Oven temperature was initially set to −22 °C for 4.7 min, then increased to 30 °C for 2.3 min to allow for elution of both gases of interest. Calibration curves were made using serial dilutions of 1 ppm N_2O and 20 ppm CH_4 (Airgas Inc.). Gas fluxes were calculated by determining the linear slope of the concentrations of the four time-points (Hutchinson and Mosier, 1981; Rochette and Bertrand, 2008). Fluxes were converted from