Biogeochemistry
https://doi.org/10.1007/s10533-020-00738-8

# A landscape approach to nitrogen cycling in urban lawns reveals the interaction between topography and human behaviors

Amanda K. Suchy · Peter M. Groffman · Lawrence E. Band · Jonathan M. Duncan · Arthur J. Gold · J. Morgan Grove · Dexter H. Locke · Laura Templeton

Received: 27 July 2020 / Accepted: 24 November 2020


**Abstract** Lawns are a common ecosystem type in human-dominated landscapes which can have negative impacts on water quality due to fertilizer applications, but also host a range of ecosystem services. While many studies have addressed water and nitrogen (N) dynamics in lawns, few have considered how topography interacts with human behaviors to control these dynamics. Our overarching objective was to determine if mesoscale topography (hillslopes within lawns) interacts with human behavior (fertilizer use) influencing patterns of N mobilization and removal in lawns. To that end, we measured several hydrobiogeochemical characteristics associated with N dynamics along topographic gradients in fertilized and unfertilized residential and institutional lawns. We found topographic gradients affect the hydrobiogeochemistry of lawns, with significant effects of landscape position (top versus toe slope versus bottomland swales), but with direction and strength of the effect often varying among different lawn types (exurban versus suburban front yards versus suburban backyards versus institutional). Fertilizer application did not affect the hydrobiogeochemical properties of lawns. Rather, results from this study suggest lawns in suburban front yards were at greatest risk of N

Responsible Editor: Stuart Grandy.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10533-020-00738-8.

A. K. Suchy (✉) · P. M. Groffman · L. Templeton
Environmental Sciences Initiative, Advanced Science Research Center At The Graduate Center, City University of New York, 85 Saint Nicholas, Terrace, New York, NY 10031, USA
e-mail: asuchy@gc.cuny.edu

A. K. Suchy · P. M. Groffman
Cary Institute of Ecosystem Studies, 2801 Sharon Turnpike, Millbrook, NY 12545, USA

L. E. Band
Department of Environmental Science, and Engineering Systems and Environment, University of Virginia, Charlottesville, VA 22904, USA

J. M. Duncan
Department of Ecosystem Science and Management, Pennsylvania State University, University Park, PA 16802, USA

A. J. Gold
Department of Natural Resources Science, University of Rhode Island, Kingston, RI 02881, USA

J. M. Grove · D. H. Locke
USDA Forest Service, Northern Research Station, Baltimore Field Station, Suite 350, 5523 Research Park Drive, Baltimore, MD 21228, USA

Published online: 03 January 2021

mobilization due to a complex suite of characteristics including proximity to impervious surfaces, swales with low saturated infiltration rates, and potential vulnerability to N deposition from vehicles. This study highlights the need to consider landscape controls of water and N fluxes and how they interact with human behaviors to better understand how these landscapes function. These results contribute to the emerging understanding of the structure, function and environmental impacts of lawns.

**Keywords** Residential lawns · Topography · Nitrogen cycling · Denitrification · Runoff

## Introduction

Urbanization affects how nitrogen (N) is processed and mobilized via water (i.e. the hydrobiogeochemistry of N) by altering soil properties, topography and hydrologic flow paths (Kaye et al. 2006), thus affecting the magnitude and the pattern of N processing in urban watersheds (Walter et al. 2000; Creed and Beall 2009). The urban environment is subdivided into parcels, introducing constructed flowpaths (e.g. gutters, downspouts, and driveways) and landscaped topography overlaid on the larger scale topography and hydrologic pathways of the neighborhood (Online Resource 1). This parcel scale topography, hereafter referred to as "mesoscale topography," can result in unique flow networks at the parcel scale. Additionally, property maintenance decisions (e.g., lawn fertilization, downspout placement) can modify soil properties, biogeochemistry, and hydrologic flow paths even further such that the hydrobiogeochemistry of parcels may differ from their nearby neighbors (Miles and Band 2015). In this study, we take a landscape approach to evaluate N mobilization and removal dynamics in lawns. N mobilization in lawns occurs when there is both a pool of reactive N and runoff or infiltrating water to move this N through the landscape. Permanent N removal occurs in locations that support denitrification, a microbial process that transforms nitrate, the dominant form of reactive N to $N_2$ gas. Understanding these dynamics is key to effectively mitigating nutrient pollution of downstream urban ecosystems. We define lawns (also known as urban grasslands) as the portion of a parcel that is "dominated by turf forming species created and maintained by humans for aesthetic and recreational purposes" (Groffman et al. 2009). Specifically, we aim to understand how mesoscale topography and fertilization practices affect the variability of hydrobiogeochemical processes and the locations of potential N mobilization and removal in lawns.

Landscape approaches to evaluation of biogeochemical fluxes have a long history in traditional ecology, as long-term depositional, hydrologic and ecosystem processes lead to the redistribution of soil, water, and nutrients across the landscape (Schimel et al. 1985; Burke et al. 1989). These processes interact to create locations that act as N sources (increase the amount of reactive N) or sinks (reduce the amount of reactive N) within a landscape. Topography has long been recognized as a key landscape factor that affects N processing at various scales. Both macrotopographic features (e.g., bottom slope positions) and microtopographic features (e.g., hollows or depressions) can accumulate substrates such as inorganic N, organic matter and moisture, but also generate anaerobic conditions that facilitate consumption of inorganic N by denitrification, thus becoming locations of N removal (Band et al. 2001; Tague et al. 2010; Duncan et al. 2013). At the same time, because these areas are often wet, they have limited capacity to support infiltration of water moving from upslope locations and can therefore become source areas for runoff, mobilizing N during large rain events (Creed and Beall 2009). These N source, sink and removal process interactions have been described in various non-urban landscapes (Vidon and Hill 2006), but have not been analyzed in lawns at the parcel scale.

Studies of N dynamics in urban landscapes typically focus on inputs and exports at the scales of neighborhoods or watersheds (Baker et al. 2001; Groffman et al. 2004; Fissore et al. 2011). Previous studies of N cycling in lawns at the parcel scale typically treated the lawn within a parcel as hydrobiogeochemically homogenous despite natural and constructed topographic gradients within parcels that can affect N source, sink and removal processes (Zhou and Troy 2008; Cook et al. 2012; Martinez et al. 2014; Locke et al. 2018a). For example, in Baltimore, MD USA, it is recommended that parcels are landscaped to slope away from the house (at a 5% grade) to prevent basement flooding, creating predictable patterns of uphill locations and small swales within parcels

(Online Resource 1). At neighborhood scales, both natural topography and landscaping interact to generate topographic features that move water and substrates across parcel boundaries causing variability in soil moisture, water flow paths, and consequently locations of N sources, sinks and removal (Online Resource 1).

In addition to incorporating natural and constructed topographic features, urban landscapes have additional factors influencing landscape patch structure and function (e.g. N mobilization and removal) that are absent in less human-dominated ecosystems (Cadenasso et al. 2008). For example, while topography or distance from streams are often useful factors for analyzing biogeochemical processes, factors such as homeowner characteristics, distance to impervious surface, or interventions to achieve social and environmental objectives must also be considered in the urban environment (Spence et al. 2012; Hobbie et al. 2017; Reisinger et al. 2018; Locke et al. 2018b). Further, built infrastructure and management decisions can alter water and solutes movement through the urban landscape. At watershed and neighborhood scales, stormwater pipe and green infrastructure can move or retain water at large scales, interrupting or overwhelming topographic flow paths that historically controlled N dynamics. In residential parcels, decisions about fertilization or placement of rooftop downspouts create spatial and temporal dynamics in N sources, flow paths and soil wetness that are not predictable from topography or other classic landscape gradients alone (Miles and Band 2015). Microbial communities can be altered by legacies of prior agricultural land use or management decisions by homeowners further affecting N dynamics in lawns (Thompson and Kao-Kniffin 2019).

Lawns comprise the largest area of any irrigated crop in the United States (Milesi et al. 2005) and can be highly and variably fertilized (Groffman et al. 2016) with fertilizer comprising up to 50% of N inputs in watershed N budgets (Baker et al. 2001; Groffman et al. 2004; Hobbie et al. 2017). Interestingly, however, studies at plot and watershed scales have found exports of fertilizer-derived N to be lower than expected for their inputs (Petrovic 1990; Gold et al. 1990; Groffman et al. 2009; Kaushal et al. 2011), demonstrating that lawns have a high potential to retain N while still "leaking" fertilizer-derived N into the environment. Thus, understanding N mobilization and removal dynamics in lawns has implications for more effective mitigation of N pollution to downstream ecosystems. Notably, most studies of N retention in lawns do not encompass variation arising from topographic gradients or the diverse use and management of these spaces (Gold et al. 1990; Raciti et al. 2008; Cook et al. 2012; Locke et al. 2018a). These considerations suggest the potential of N export within lawns may be influenced by hotspots (small areas that generate a large proportion of exported N) and hot moments (brief periods of time that generate a large proportion of exported N) that have been missed in previous sampling campaigns.

The purpose of this study was to address this gap in past research. Thus, we examined lawns that varied in multiple social, soil, and parcel-size factors within two residential settings and one institutional setting in Baltimore, MD USA to determine if (a) mesoscale topography (e.g. hillslopes within a parcel) can provide an organizing template of hydrobiogeochemical patterns associated with N mobilization and removal processes for different lawn types; and (b) compared fertilized and unfertilized lawns to determine if fertilization practices overwhelm hydrobiogeochemical patterns expected to be influenced by topography. Our specific objectives were to determine (1) if basic topographic patterns observed in less human-dominated systems are expressed in urban landscapes, with top, middle, and bottom slope positions having unique hydrobiogeochemical characteristics; (2) if hydrobiogeochemical properties of lawns are more variable within a lawn or among lawns within a neighborhood; (3) if homeowner fertilizer applications homogenize hydrobiogeochemical properties of lawns, thus overwhelming the influence of topography on these processes; and (4) if hydrobiogeochemical characteristics expected to generate hotspots of N mobilization (e.g. low infiltration and denitrification rates) or hotspots of N removal (e.g. high infiltration and denitrification rates) co-occur in predictable locations, such as swales, in lawns.

## Methods

### Site description

The lawns in this study were located in Baltimore County, Piedmont region of Maryland, USA, and included four different lawn types: exurban, suburban front yard, suburban backyard, and institutional. Four sites (parcels) were located in the Baisman Run watershed (hereafter exurban lawn type), five in the Dead Run watershed (hereafter suburban lawn types), and two on the University of Maryland Baltimore County campus (hereafter institutional lawn type; Fig. 1). Average annual precipitation is approximately 1030 mm, distributed evenly throughout the year (World Climate, http://www.worldclimate.com/climate/us/maryland/baltimore).

The exurban lawns are located in Baisman Run, a 3.82 $km^2$ watershed about 10 km north of Baltimore City. Land cover in Baisman Run consists of 81.8% tree canopy, 4.8% impervious surfaces (including structures and roads) and 14.3% low vegetation (including lawns and tilled fields; Lagrosa and Welty 2017). The residential areas are characterized by large homes and large ($\sim$ 1 ha) lots, often dominated by lawns (Fig. 1, bottom left). Baisman Run has limited stormwater infrastructure, lacks public water supplies, and household wastewater is processed by on-site septic systems. The Baisman Run watershed is underlain by micaceous schist (Cleaves et al. 1970; Wolman 1987). Soils at the study parcels are dominated by either acidic, low fertility Manor loams consisting of loam and sandy loam texture soils, or Glenelg loam consisting of loam and clay loam texture soils (Groffman et al. 2006, NRCS, https://websoilsurvey.nrcs.usda.gov/). The study hillslopes ranged in length from 6 to 12 m (estimated distance from top transect to swale transect) with a mean slope of approximately 10%.

The suburban lawns are located in Dead Run, a 14.11 $km^2$ watershed in Baltimore County near the Baltimore City limits and is tributary to the Gwynns Falls. The Gwynns Falls empties to Baltimore Harbor, which drains into the Chesapeake Bay. Landcover in Dead Run consists of 27.6% tree canopy, 47.4% impervious surfaces (including structures and roads) and 26.2% low vegetation (including lawns and tilled fields; Lagrosa and Welty 2017). Residential areas in


**Fig. 1** Map of neighborhood sampling site locations

Dead Run are dominated by small houses on small (~ 0.1 ha) lots serviced by sanitary sewers with most of the areas developed decades before stormwater regulations were adopted (Fig. 1, bottom middle). Dead Run watershed is underlain by amphibolite and ultramafic complex rocks (Groffman et al. 2006). Soils at the study parcels are derived from diabase and are classified as a more base rich Mount Lucas-Urban land complex consisting of silt loam and clay loam texture soils (NRCS, https://websoilsurvey.nrcs.usda.gov/). The study hillslopes ranged in length from 4 to 10 m, with a mean slope of approximately 7%.

Institutional lawns are located on the University of Maryland, Baltimore County (UMBC, Fig. 1, bottom right). Soils at the study parcels are classified as urban land soils (NRCS, https://websoilsurvey.nrcs.usda.gov/). The study hillslopes ranged in length from 4 to 18 m with a mean slope of approximately 11%.

Homeowners self-reported whether they fertilized in the last year or not (answered as "yes" or "no"). In the exurban neighborhood, two homeowners reported that their lawns were fertilized by a commercial lawn care company, while two reported no fertilizer use. In the suburban neighborhood, three homeowners reported they fertilized their lawns themselves, while two reported no fertilizer use. We did not collect details on amounts or timing of fertilizer applications in the exurban or suburban neighborhoods. The institutional lawns were uniformly managed and fertilized (~ 100 kg N/ha/year) by campus maintenance staff. Previous studies have found that roughly 50% of homeowners fertilize their lawns in the Baltimore area (Fraser et al. 2013). Lawns at the study sites are dominated by one or two of the following cool season perennial grasses: *Poa pratensis* (Kentucky blue grass), *Festusca arundinacea* (tall fescue), *Lolium perenne* (perennial ryegrass), and *Festusca rubra* (red fescue).

## Sampling design

At each site, we identified a hillslope on which we systematically sampled to include distinct topographic positions: top, toe, and swale of the hillslope (Fig. 2). Tops were located on the upper beginning of a hillslope. The toes were located either on sloped locations directly above a swale or at locations where hillslopes terminated at impervious surface and no swale was present (a configuration specific to front

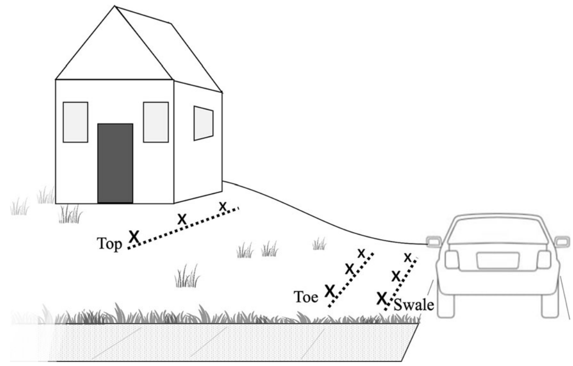


**Fig. 2** Example of sampling design on one hillslope (transect and sampling locations) in a suburban front yard. Transects were a maximum 10 m in length. Not all hillslopes were adjacent to impervious surfaces, but sampling design remained the same

lawns in the suburban neighborhood; Online Resource 2). Swales were located at the flattened portion of the bottom of the hillslope where it appeared water would pool during a rain event (Fig. 2). In the suburban neighborhood, we identified one hillslope in the front of the house (front yard), and one behind the house (backyard), as these locations may be distinct in their use, management, and topography (Locke et al. 2018b). In the exurban neighborhood and institutional sites, we sampled from one hillslope per parcel as there were no distinct front or back lawns at these sites. In total, we sampled from 16 different hillslopes, establishing a transect (10 m maximum) along each of the topographic gradients (top, toe and swale). Along each transect we selected three sampling locations for a total of nine locations per hillslope (Fig. 2), for the total of 144 sampling locations.

At each sampling location we took two soil cores to 10 cm depth in September and October 2017. We measured saturated infiltration rates (N = 139) using Cornell Sprinkler Infiltrometers (hereafter infiltrometer) at the same soil sampling locations in October 2017 at 14 of the study hillslopes and completed the final two study hillslopes in January and February 2018 (this seasonal change did not affect the infiltrometer measurements). We lost 5 infiltrometer sampling locations due to tree roots or driveway construction that impeded the installation of the infiltrometers.

## Soils

Soil cores were collected, stored on ice in the field, and then stored at 4 °C in the lab until processing for soil physical and chemical characteristics. The two soil cores collected from the same sampling location were combined, homogenized, and roots and rocks were removed, yielding 144 unique soil samples. Soil moisture was determined gravimetrically by drying a subsample of soils for 48 h at 60 °C. Soil organic matter was determined by mass loss on ignition for 4 h at 450 °C. Soil nitrate ($NO_3^-$) and ammonium ($NH_4^+$) was determined by shaking 7.5 g (wet weight) soil with 30 mL 2 M KCl for 1 h. KCl extract was then filtered through pre-leached Whatman 42 ashless filters and stored at 4 °C until analyzed colorimetrically on a Lachat QC8000 flow-injection analyzer.

Net nitrogen mineralization was determined by incubation of 10 g (wet weight) soil for 10 days in 946 mL "mason" jars. After the incubation period, soil $NO_3^-$ and $NH_4^+$ were extracted by shaking with 40 mL 2 M KCl for 1 h. KCl extract was collected and analyzed for $NO_3^-$ and $NH_4^+$ as described above. Net nitrogen mineralization was calculated as the change in soil $NH_4^+$ plus the change in soil $NO_3^-$ over the 10 day incubation period.

Potential denitrification (DNP) was measured using denitrification enzyme assays (Groffman et al. 1999). Five grams of soil (wet weight) were added to 125 mL Erlenmeyer flasks and 10 mL of media amended with $NO_3^-$ (200 mg $NO_3$-N kg soil$^{-1}$ as $KNO_3$) and carbon (400 mg C kg soil$^{-1}$ as glucose) was added to alleviate $NO_3^-$ and carbon limitation of denitrifying microbes. We also assessed what substrates ($NO_3^-$ or carbon) limited denitrification by conducting factorial media amendments with media containing only $NO_3^-$, only carbon, or neither (DI only). Flasks were flushed with $N_2$ gas to generate the anaerobic conditions necessary for denitrification and 5 mL of acetylene was added to block the reduction of $N_2O$ to $N_2$ (Groffman et al. 1999). Gas samples were collected at 30 and 90 min and were analyzed on a Shimadzu GC2014 gas chromatograph for $N_2O$ concentration.

## Saturated infiltration rate measurements

We measured saturated infiltration rates using Cornell Sprinkle Infiltrometers (Ogden et al. 1997). Infiltrometers consist of a small rainfall simulator placed on an infiltration ring (457.3 cm$^2$) with a hole and tubing that allows for the runoff generated during the simulated rainfall to be collected in a beaker. Rainfall simulations in this study were run at a very high rainfall rate between 20–30 cm/h. Rainfall of this intensity is rarely observed; however, for the infiltrometer method, high rainfall rates are necessary to achieve saturated conditions to get an adequate estimate of saturated infiltration rates. To achieve saturation, simulated rainfalls lasted a minimum of 45 min or until saturated conditions were achieved, defined as stable runoff over 9 min (Cornell Sprinkle Infiltrometer, http://soilhealth.cals.cornell.edu/cornell-sprinkle-infiltrometer/). For each simulated rainfall, we recorded initial and final soil volumetric water content using a Field Scout TDR 300 with 7.5 cm rods, time to runoff, and runoff volume and water height every 3 min.

Rainfall rate ($r$) for each simulation was calculated as:

$$r = \frac{H_1 - H_2}{t} \quad (1)$$

where $H_1$ and $H_2$ are the height of the water in centimeters in the rainfall simulator at the beginning and end of the rainfall simulation, and $t$ is the duration of the rainfall simulation in hours.

Runoff rate ($ro$) was calculated for each 3-min interval with the following equation:

$$ro = \frac{V}{A \times t_r} \quad (2)$$

in which $V$ is the volume of runoff collected during a 3-min sampling interval in milliliters. $A$ is the area of the infiltrometer ring in centimeters. $t_r$ is duration of time during which the runoff was collected (i.e. 3 min interval) in hours.

Field saturated infiltration rate ($I_{FS}$) was calculated as the difference between the rainfall rate and the runoff rate at the end of simulated rainfall when saturated conditions and steady state infiltration have been achieved; thus, $I_{FS}$ represents a more stable soil hydrologic characteristic compared to infiltration rates at ambient conditions. Because a single ring was used, a correction factor (0.8) was applied to account for three dimensional flow from the bottom of the ring (Reynolds and Elrick 1990), resulting in the following equation:

$$I_{FS} = 0.8(r - ro) \tag{3}$$

Statistical analyses

All tests were run using Stata 16 (StataCorp 2019). To account for the clustered, non-independent nature of the sampling design, we used linear mixed effects models to treat site (i.e. sampled hillslope) as a random effect, which partitions the variance explained by each site (Harrison et al. 2018). We first ran models examining only main effects of topography and fertilizer on hydrobiogeochemical properties (objectives 1 and 3), and to test for differences in these properties among lawns types (Eq. 4):

$$Y_{ij} = \gamma_{00} + \gamma_{10} hillslope_{ij} + \gamma_{01} lawntype_{0j} + \gamma_{02} fertilizer_{0j} + \mu_{0j} + e_{ij} \tag{4}$$

where $Y_{ij}$ represents the coefficient for each hydrologic and soil property variable for each sample $i$ at site $j$. $\gamma_{00}$ is the intercept. $\gamma_{10}$ is the coefficient for the categorical variable hillslope location (top, toe, swale) with top as the reference. $\gamma_{01}$ is the coefficient for the categorical variable for lawn type (exurban, suburban backyards, suburban front yard, and institutional lawns) with exurban as the reference. $\gamma_{02}$ is the coefficient for the categorical variable for unfertilized versus fertilized lawns with unfertilized as the reference. $\mu_{0j}$ represents random effects of site and $e_{ij}$ represents observation level residuals. We also report $\sigma^2$ representing the variance within sites, $\tau_{00}$ representing variance across sites, and the intraclass correlation coefficient (ICC) reflecting the proportion of the total variance accounted for by the clustering of the data in each site. Denitrification potential (DNP), net N mineralization, soil $NO_3^-$, soil $NH_4^+$ and saturated infiltration rate were log transformed to adhere to assumptions of normality.

We also ran a separate set of models to test for moderation effects. Specifically, we examined if lawn type moderated topographic effects on soil and hydrologic properties as the lawn types differed in several multiple social, soil, and parcel-size factors. Additionally, we examined if fertilizer application moderated topographic effects on soil and hydrologic properties as we expected the addition of fertilizer may homogenize soil properties, such as soil $NO_3^-$ (objective 3). Therefore, we ran the same model described above but included two interaction terms: lawn type X hill location and fertilizer use X hill location. Significant interaction terms were then included in a series of nested models and Akaike information criterion (AIC) was used to determine if the inclusion of interaction terms sufficiently improved model fit. Models with an AIC score that was lower than the main effects model by 2 or more were selected as having moderating effects on soil and hydrologic properties (Burnham and Anderson 2004).

To test if substrates limiting denitrification ($NO_3^-$ or carbon) varied by hillslope location and fertilizer use within each lawn type (objective 1) we conducted a Kruskal–Wallis H test, followed by Dunn's post-hoc test to compare limitation treatments (DI, $NO_3^-$, C, $NO_3^-$ + C).

To examine if hydrologic and soil properties were homogenous within and among lawns (objectives 2), we calculated coefficients of variation (CV; standard deviation/mean × 100) for each study hillslope (within lawns) and each fertilized and unfertilized yard type (among lawns). CVs were calculated for DNP, soil $NO_3^-$, soil $NH_4^+$, soil organic matter, soil moisture and saturated infiltration rate. Net N mineralization and pH were omitted as these data are not on a ratio scale and thus would generate inappropriate CVs. Homogenous variables within or among lawns were defined as a CV below 100%. To determine if homeowner fertilization of lawns homogenized hydrologic and soil variables (objective 3), we conducted a t-test comparing fertilized and unfertilized lawns using CVs of soil and hydrologic variables for each study hillslopes as the dependent variable.

To examine if particular hydrobiogeochemical characteristics associated with N retention or mobilization co-occurred in predictable locations, we examined where sampling locations fell on both $NO_3^-$ retention (DNP) and $NO_3^-$ mobilization (saturated infiltration rate) axes (objective 4). To identified sampling locations we expected may act as hotspots of N mobilization or retention, we identified sampling locations that fell in the upper and lower quartiles (i.e. the extremes) for both axes (Palta et al. 2014). The sampling locations that occurred at these extremes were categorized into four groupings:

Group 1: sampling locations with LOW DNP and LOW saturated infiltration rates.

Group 2: sampling locations with LOW DNP and HIGH saturated infiltration rates.

Group 3: sampling locations with HIGH DNP and LOW saturated infiltration rates.

Group 4: sampling locations with HIGH DNP and HIGH saturated infiltration rates.

We defined locations with a high potential for $NO_3^-$ retention as having both high DNP and high saturated infiltration rates (group 4). Locations defined as having high potential for $NO_3^-$ mobilization had low DNP and low saturated infiltration rates (group 1). Locations with low DNP and high saturated infiltration rates (group 2) and high DNP and low saturated infiltration rates (group 3) have the potential to act as locations of either $NO_3^-$ retention or $NO_3^-$ mobilization given runoff conditions. We performed a chi-square test to determine if certain groups were more likely to contain sampling locations from particular hillslope locations, lawn types or lawn fertilization practices.

## Results

### Main effects of topography, lawn type, and fertilizer use on soil and hydrologic properties (objective 1)

Results of mixed effects models revealed a significant effect ($p < 0.05$) of topography (i.e. hillslope location) on soil organic matter ($\chi^2$ (2) = 9.13), pH ($\chi^2$ (2) = 12.42), and saturated infiltration rate ($\chi^2$ (2) = 8.76; Table 1). Specifically, soil organic matter and pH were significantly greater in toes and swales compared to tops of hillslopes, while saturated infiltration rates were significantly lower in swales than toes and tops of hillslopes (Fig. 3).

The same models also revealed a significant effect ($p < 0.05$) of lawn type on DNP ($\chi^2$ (3) = 8.33), soil $NH_4^+$ ($\chi^2$ (3) = 14.83), soil organic matter ($\chi^2$ (3) = 32.96), pH ($\chi^2$ (3) = 11.51), and saturated infiltration rate ($\chi^2$ (3) = 8.63; Table 1), and a marginally significant effect on soil $NO_3^-$ ($p = 0.08$, $\chi^2$ (3) = 6.68). Specifically, DNP and soil organic matter were significantly higher in suburban lawns compared to exurban lawns (Fig. 4). Soil organic matter was also significantly higher in suburban lawns than institutional lawns (Fig. 4). Soil $NH_4^+$ was significantly higher in suburban backyard lawns compared to all other lawn types, while pH was significantly lower in suburban backyard lawns compared to exurban and institutional lawns (Fig. 4). Institutional lawns also had significantly higher saturated infiltration rates than all other lawns (Fig. 4).

Lawns on which the homeowner reported they fertilize had significantly greater ($p < 0.05$) net mineralization ($\chi^2$ (1) = 3.85) and soil $NO_3^-$ ($\chi^2$ (1) = 18.01), and marginally significantly higher soil $NH_4^+$ ($p = 0.06$, $\chi^2$ (1) = 3.7; Table 1, Fig. 5).

### Moderating effects of lawn type and fertilizer use on soil and hydrologic properties

Mixed effects models revealed lawn type significantly ($p < 0.05$) moderated effects of topography on several soil and hydrologic properties, and also improved model fit (Online Resource 3). Lawn type moderated the effect of topography on outcomes for DNP ($\chi^2$ (11) = 45.12), soil $NO_3^-$ ($\chi^2$ (11) = 34.03), soil organic matter ($\chi^2$ (11) = 41.91), soil moisture ($\chi^2$ (11) = 29.58), and saturated infiltration rate ($\chi^2$ (11) = 43.11). We found fertilizer use did not moderate topographic effects on any soil or hydrologic property. Main effects models remained the most parsimonious model for net mineralization, soil $NH_4^+$, and pH (Online Resource 3). Specifically, we found that DNP was higher on lower slope (toes and swales) than top slope positions for all lawn types except exurban lawns where it was significantly lower in swales (Fig. 6). Soil $NO_3^-$ was significantly higher in toes and swales than top positions in institutional lawns, but topography did not have a significant effect on soil $NO_3^-$ in any other lawn type (Fig. 6). Soil organic matter, similar to the main effects model, increased from top to bottoms of hillslopes for all lawn types except suburban backyards where swales had lower soil organic matter than other hillslope positions (Fig. 6). Soil moisture had different topographic patterns depending on lawn type with soil moisture increasing from top to bottoms of hillslopes at the exurban and institutional sites and showing no distinct pattern at the suburban sites (Fig. 6). For saturated infiltration rates, we found that the significantly lower saturated infiltration rates in swales found in the main effects model were driven by very low saturated infiltration rates in swales of suburban front yards specifically (Fig. 6).

**Table 1** Mixed effect model results for models including only main effects

| | DNP b (SE) | N min b (SE) | $NO_3^-$ b (SE) | $NH_4^+$ b (SE) |
|---|---|---|---|---|
| Fixed effects | | | | |
| Intercept | 4.23 (0.51)*** | 1.71 (0.06)*** | 1.66 (0.29)*** | − 0.82 (0.31)** |
| Hill location: top as reference | | | | |
| Toe | 0.46 (0.26)† | 0.10 (0.06)† | 0.11 (0.10) | − 0.43 (0.23)† |
| Swale | 0.27 (0.26) | 0.07 (0.06) | 0.15 (0.10) | − 0.35 (0.23) |
| Lawn type: exurban as reference | | | | |
| Suburban BY | 1.64 (0.58)** | 0.08 (0.06) | − 0.43 (0.33) | 0.87 (0.34)** |
| Suburban FY | 1.14 (0.58)* | 0.01 (0.06) | 0.37 (0.33) | 0.18 (0.34) |
| Institutional | 1.00 (0.78) | − 0.04 (0.09) | − 0.16 (0.45) | − 0.63 (0.45) |
| Fertilize: unfertilized as reference | | | | |
| Fertilized | − 0.56 (0.46) | 0.10 (0.05)* | 1.14 (0.27)*** | 0.52 (0.27)† |
| Random effects | | | | |
| $\sigma^2$ | 0.56 | 1.52e−9 | 0.22 | 0.11 |
| $\tau_{00,\ site}$ | 1.61 | 0.08 | 0.26 | 1.21 |
| $N_{site}$ | 16 | 16 | 16 | 16 |
| $ICC_{site}$ | 0.37 | 0.04 | 0.45 | 0.23 |
| Observations | 144 | 143 | 144 | 143 |

| | Organic matter b (SE) | Soil moisture b (SE) | pH b (SE) | Sat. inf b (SE) |
|---|---|---|---|---|
| Fixed effects | | | | |
| Intercept | 5.55 (0.35)*** | 19.19 (2.03)*** | 6.44 (0.28)*** | 1.16 (0.33)*** |
| Hill location: top as reference | | | | |
| Toe | 0.64 (0.23)** | 0.55 (0.72) | 0.18 (0.08)* | 0.00 (0.12) |
| Swale | 0.57 (0.23)* | 0.93 (0.72) | 0.29 (0.08)*** | − 0.33 (0.13)** |
| Lawn type: exurban as reference | | | | |
| Suburban BY | 1.56 (0.38)*** | − 2.50 (2.36) | − 1.01 (0.33)** | 0.64 (0.38)† |
| Suburban FY | 1.57 (0.38)*** | − 0.52 (2.36) | − 0.52 (0.33) | 0.45 (0.38) |
| Institutional | − 0.33 (0.51) | − 5.83 (3.18)† | − 0.04 (0.44) | 1.47 (0.51)** |
| Fertilize: unfertilized as reference | | | | |
| Fertilized | 0.49 (0.31) | 2.21 (1.90) | − 0.21 (0.26) | 0.23 (0.31) |
| Random effects | | | | |
| $\sigma^2$ | 0.17 | 10.86 | 0.22 | 0.28 |
| $\tau_{00,\ site}$ | 1.31 | 12.44 | 0.16 | 0.40 |
| $N_{site}$ | 16 | 16 | 16 | 16 |
| $ICC_{site}$ | 0.38 | 0.53 | 0.69 | 0.57 |
| Observations | 144 | 144 | 142 | 139 |

DNP, N min, $NO_3^-$ $NH_4^+$, saturated infiltration rate data are log transformed

*DNP* denitrification potential, *N min* net N mineralization, *$NO_3^-$* soil nitrate, *$NH_4^+$* soil ammonium, *Sat. inf.* saturated infiltration rate, *BY* backyard, *FY* front yard

†Trending $p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; b = regression coefficient; SE = standard error

## Limiting substrates for denitrification (objective 1)

Factorial amendments of DEA media with $NO_3^-$ and carbon revealed widespread evidence of carbon limitation of denitrification potential at all study sites. Specifically, the Kruskal–Wallis H test showed significant ($p < 0.001$) differences among the tests for substrates limiting DNP (DI, $NO_3^-$, C, $NO_3^-$ + C) for all lawn types (Exurban, $\chi^2$ (3) = 124.9; Suburban backyard, $\chi^2$ (3) = 161.6; Suburban front yard, $\chi^2$ (3) = 149.9; Institutional, $\chi^2$ (3) = 47.1). Dunn's post hoc comparisons revealed all lawn types were carbon

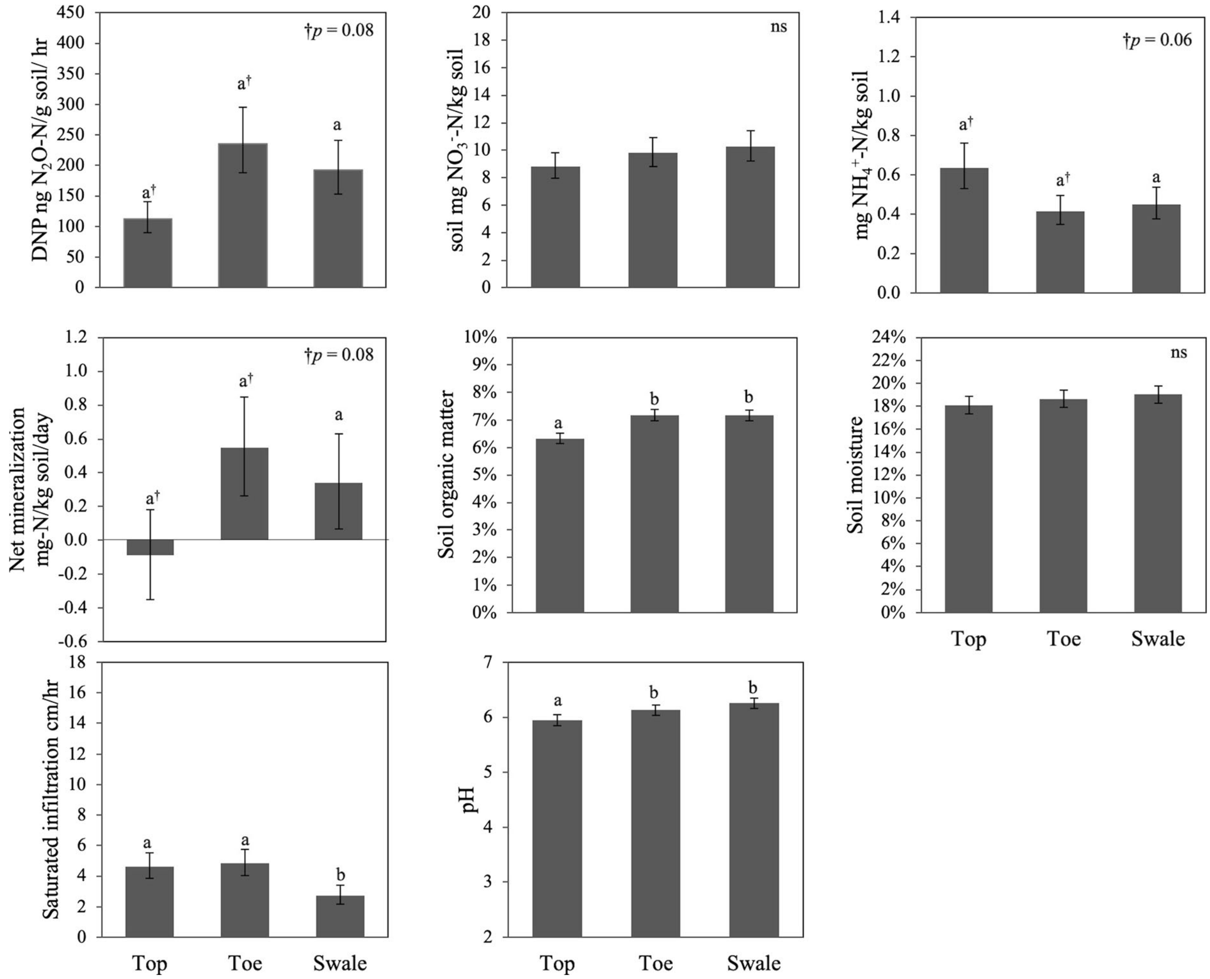


**Fig. 3** Mean values for soil properties and hydrologic variables by hillslope location. Different letters represent significant differences ($p < 0.05$). Pairwise trending differences are represented by $^{\dagger}(p < 0.10)$. Error bars indicate $\pm$ 1 SE

limited (Fig. 7). Additional Kruskal–Wallis and Dunn's post hoc tests were conducted to examine if limiting substrates for denitrification differed among hillslope locations and among fertilizer treatments; all permutations revealed carbon limitation.

## Hydrobiogeochemical homogeneity within and among lawns (objective 2 and 3)

Using CV as an estimate of variability (i.e. homogeneity), we found that hydrologic and soil properties demonstrated different patterns of homogeneity within and among lawns of a shared lawn type. Saturated infiltration rates, DNP and soil $NH_4^+$ were more heterogenous (defined as a CV above 100) within and among lawns than soil $NO_3^-$, soil organic matter or soil moisture (Fig. 8). Typically, within and among lawn CV patterns were similar (i.e. variables that were homogenous within lawns were also homogenous among lawns) with two exceptions: DNP and saturated infiltration rates. Both of these variables overall demonstrated more heterogeneity among lawns of a particular lawn type than within lawns. T-tests found no significant difference between CVs of fertilized and unfertilized lawns for any hydrologic or soil property suggesting homeowner fertilization does not have a homogenizing effect on the measured variables.

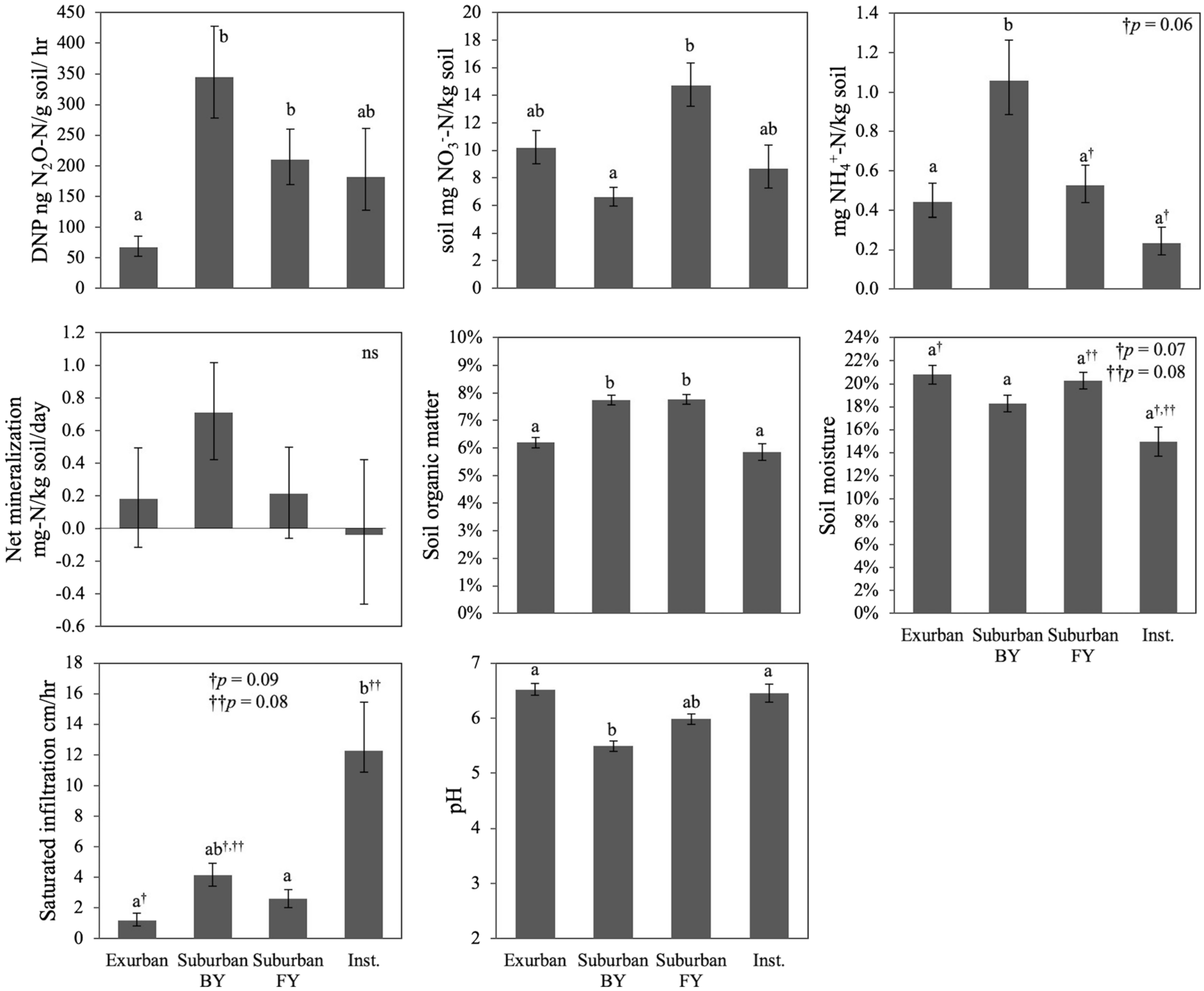

**Fig. 4** Mean values for soil properties and hydrologic variables by lawn type. Different letters represent significant differences ($p < 0.05$). Pairwise trending differences are represented by †($p < 0.10$). *BY* backyard, *FY* front yard. Error bars indicate ± 1 SE

## Potential hotspots of $NO_3^-$ mobilization and retention (objective 4)

We found that 42 of the 144 sampling locations fell into one of the four groups based on the upper and lower quartiles of DNP and saturated infiltration rates. Groups varied significantly by lawn type ($\chi^2$ (9) = 56.88), $p < 0.001$), were marginally significant by hillslope location ($\chi^2$ (6) = 11.07, $p = 0.09$) and showed no significant effect of fertilizer use ($\chi^2$ (3) = 5.7, $p = 0.13$). Specifically, we found that 85% of the sampling locations occurring in group 1 (low DNP, low infiltration; high potential for $NO_3^-$ mobilization) were from 2 of the 4 hillslopes sampled in the exurban neighborhood, with no differences among hillslope location and fertilizer use (Fig. 9). In group 2 (low DNP, high infiltration), 77% of the sampling locations were from the tops and toes of hillslopes in 3 of the 5 suburban front yards sampled (Fig. 9). In group 3 (high DNP, low infiltration), 83% of sampling locations were from toes and swales in 6 of the 10 suburban neighborhood front and backyard hillslopes sampled (Fig. 9). In group 4 (high DNP, high infiltration; high potential $NO_3^-$ retention) 85% of sampling locations came from the institutional lawns with most sampling locations occurring on one study hillslope (Fig. 9).

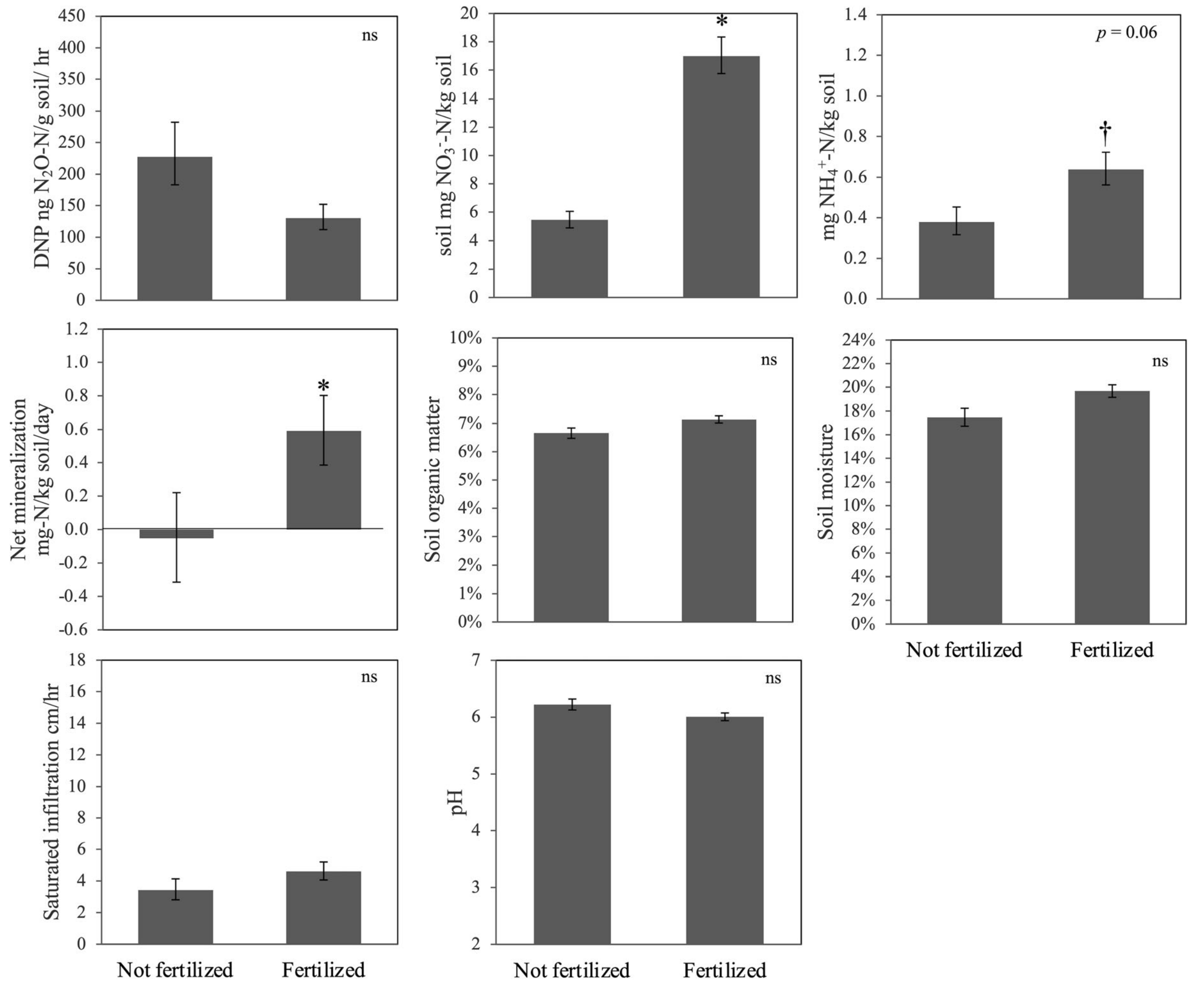


**Fig. 5** Mean values for soil properties and hydrologic variables by fertilizer use. Different letters represent significant differences. Pairwise trending differences are represented by †($p < 0.10$). Error bars indicate ± 1 SE

## Discussion

Lawns are often the target of N mitigation plans as they are a significant component of landcover and account for a large portion of the N inputs in urban watersheds due to fertilizer applications. While several studies show lawns are relatively retentive of N given these large N inputs (Gold et al. 1990; Raciti et al. 2008), it is not clear if lawns can be treated as hydrobiogeochemically homogenous, or if there are locations that may be more retentive of N than others. The present study examined if topographic gradients and anthropogenic inputs of N via fertilizer affect hydrobiogeochemical patterns of N sources, sinks and removal in lawns. Key findings for this study are:

(1) Topography has an effect on some hydrobiogeochemical characteristics of lawns, such as soil organic matter, soil moisture, and saturated infiltration rates, just as it does in non-urban landscapes (objective 1). However, differences among lawns types (e.g., exurban vs. suburban; front yard vs. backyard) in the direction or strength of change, when moving from the top to the bottom of the hillslope, suggest both natural and anthropogenic factors seem to influence the effect topography has on hydrobiogeochemical characteristics of lawns.

(2) Front and back lawns of suburban neighborhoods varied in several hydrobiogeochemical properties, such as higher soil $NO_3^-$ and lower

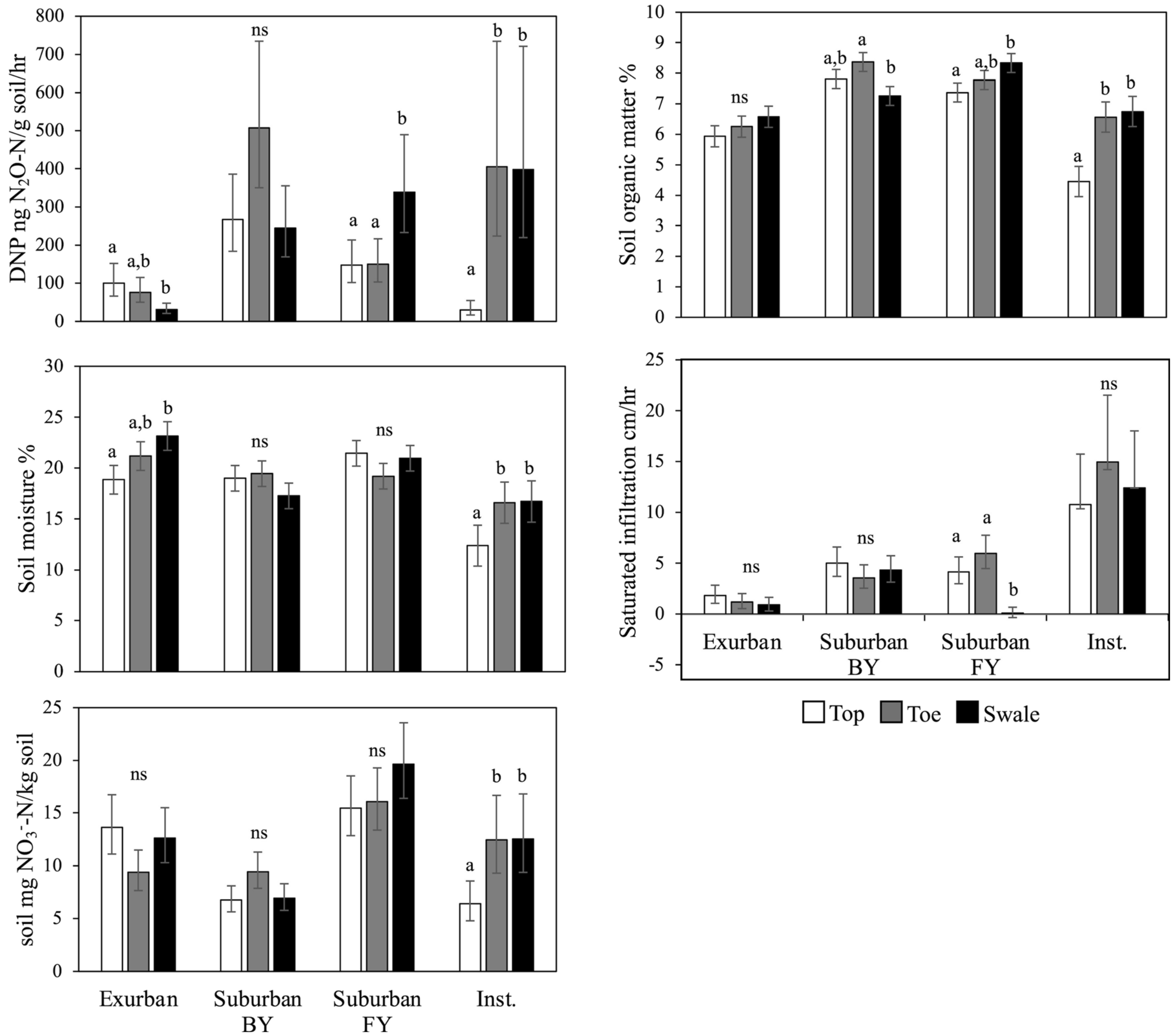


**Fig. 6** Effects of topography on DNP, soil organic matter, soil moisture, saturated infiltration rate and soil $NO_3^-$ as moderated by lawn type and effects of fertilizer on soil $NO_3^-$ as moderated by lawn type. Significance tests ($p < 0.05$) are made within lawn types. Astericks (*) or different letters denote significant differences. Non-significant comparisons are denoted by ns. Institutional lawns are all fertilized and do not have an unfertilized comparison group. *BY* backyard, *FY* front yard. Error bars indicate ± 1 SE

swale saturated infiltration rates in front yards compared to backyards. This suggests these spaces may be utilized or managed differently by homeowners. However, whether a homeowner fertilizes or not has limited effects on hydrobiogeochemical properties of lawns (objective 3) suggesting the need to better understand other aspects of lawn use and management that may affect N dynamics.

(3) Hydrobiogeochemical properties of lawns related to N mobilization and removal, such as DNP and saturated infiltration, are variable within and among lawns (objective 2). This suggests that lawns may have locations that are more or less susceptible to mobilizing N during rain events (objective 4).

(4) Carbon limitation of denitrification potential in lawns suggests these ecosystems may have the potential to remove more N via denitrification with mitigation strategies targeted at increasing soil carbon.

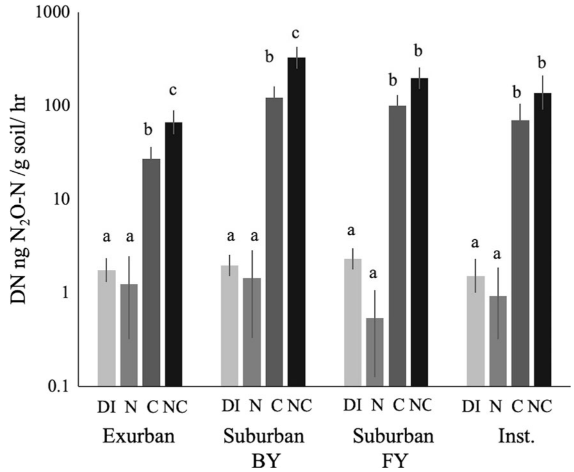


**Fig. 7** Mean denitrification (DN) rates for limitation treatments each lawn type. DI = distilled water addition; N = $NO_3^-$ addition; C = carbon addition; NC = $NO_3^-$ and carbon addition. Different letters denote significant differences from nonparametric Dunn's pairwise comparison tests at $p < 0.05$. *BY* backyard, *FY* front yard, *Inst* institutional. Error bars indicate ± 1 SE. Note log scale

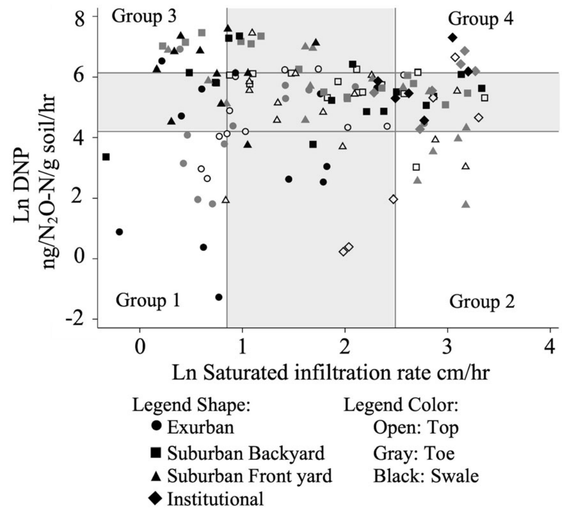


**Fig. 9** Scatter plot of sampling locations along a hydrologic (saturated infiltration rate) and denitrification gradient. Groups represent sampling locations that fall at the extremes (defined as the upper or lower quartile of the data distribution) of both axes

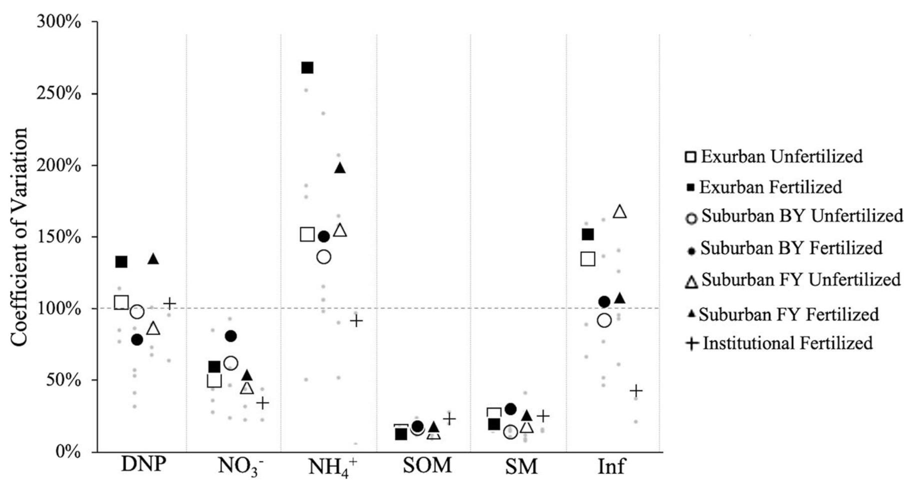


**Fig. 8** Within and between lawn coefficients of variation (CV) of soil and hydrologic properties. Large, black symbols represent between lawn CVs for each fertilized and unfertilized lawn type. Small, gray symbols represent within lawns CVs for given lawn type. *BY* backyard, *FY* front yard, *DNP* potential denitrification, *$NO_3^-$* soil $NO_3^-$, *$NH_4^+$* soil $NH_4^+$, *SOM* soil organic matter, *SM* soil moisture, *Inf* saturated infiltration rate

Together these results provide a basis for management recommendations about mitigating N mobilization and improving N removal.

## Topography affects soil and hydrologic properties, but so do people

Topography has long been recognized as a useful organizing principle for hydrobiogeochemical processes (Schimel et al. 1985; Amundson and Jenny 1997; Band et al. 2001) generating predictable patterns of water movement downslope and accumulation of N and organic matter in low lying locations. Our data suggest that these inherent topographic controls are also expressed in urban areas, but not uniformly. Organic matter, soil $NO_3^-$ and DNP are higher in lower slope positions in some, but not all, lawn types (Figs. 3 and 6).

Notably, lawn type frequently moderated the effect of topography on hydrobiogeochemical properties in lawns. However, determining precisely why lawn type moderated the effect of topography on hydrobiogeochemical properties in lawns is difficult due to several differences among the exurban, suburban and institutional lawn types including, but not limited to, underlying topography, soil types, land use legacies, homeowner use and management, and time since home construction. While our results suggest that the effect of natural topographic gradients may be interacting with either the built environment or people's use/management of their lawns, more research is needed to determine if this is generalizable to other lawns in other cities. Below we propose a few possible explanations for how different aspects of lawns may interact with topography at our study sites.

Parcel size, and thus the size of the hillslope, could affect the magnitude of the impact that topography has on hydrobiogeochemical properties of lawns. In this study, exurban and institutional parcels were larger than the suburban neighborhood parcels ($\sim$ 1 ha vs. 0.1 ha parcels, respectively) and the hillslopes were generally steeper. The larger parcel size likely reduced the impact of initial housing construction and constructed drainage (roads, sewers) and thus left more of the natural topography in place compared to the suburban lawns; consequently, patterns expected from topographic gradients, such as soil moisture, remain prevalent (Fig. 6). In contrast, the smaller suburban parcels are likely more impacted from housing construction, constructed drainage and human use. For example, impacts from downspout placement or shading from the house would have a proportionally larger impact on soil moisture patterns on small parcels compare to large ones (Online Resource 2); consequently, soil moisture would be higher on the tops of hillslopes making them more similar to swale locations and masking the effect of topography. Additionally, the very low saturated infiltration rates in swales in suburban front yards could be the result of how people use their front yards (Fig. 6). These swales are located adjacent to driveways where people are frequently accessing their cars. This activity may compact the soil in these very specific locations resulting in extremely low saturated infiltration rates (Online Resource 1).

The low organic matter content of swales of suburban backyards is an unexpected result, as these tended to be larger swales compared to swales on other lawn types and thus could be receiving more upslope inputs. However, this could be the result of how these particular swales function during large rain events. Rather than functioning as a depression that accumulates organic matter (Schimel et al. 1985; Duncan et al. 2013), these backyard swales may be more analogous to ephemeral streams, with water flowing through them and across parcels during large rain events. Organic matter may become entrained during such storms and deposited in a different location (Online Resource 1c).

It is also likely that underlying differences in soil types and land use legacies affected how topography influenced hydrobiogeochemical properties among different lawn types. For example, the exurban lawns in this study have micaceous schist-derived soils, which have inherently lower fertility than the diabase-derived soils of the suburban neighborhood (Groffman et al. 2006). Additionally, the exurban parcels were converted from agricultural to residential use more recently than the suburban parcels (1990s versus 1960s respectively), and thus erosion may further contribute to lower fertility in the exurban neighborhood. These underlying factors in the exurban yards may have current and legacy effects on the soil microbial community, potentially explaining why DNP was much lower in exurban lawns and did not increase in bottom slope locations despite observations of higher soil moisture or soil organic matter; two soil properties typically associated with higher DNP.

While we do not address differences in microbial communities among the lawns in this study, it is likely that differences in microbial communities are affecting N dynamics in lawns. Previous studies have found that microtopography affects microbial community composition in seemingly homogenous agriculture fields (Suriyavirun et al. 2019). In addition, land use legacies and homeowner management decisions, such as whether to apply fertilizer or return mowed clippings to the lawn, can have impacts on lawn carbon and N dynamics and likely the associated microbial communities (Thompson and Kao-Kniffin

2019). A better understanding of lawn microbial communities could provide mechanistic insight into how topographic gradients interact with the built environment to shape N dynamics.

## Differences in front and backyard lawns in the suburban neighborhood

Suburban front and backyard lawns have unique landscape configurations relative to each other, and to exurban and institutional lawns; these differences in configuration likely have complex effects on N processes. As mentioned above, the suburban lawns have smaller parcel sizes than the exurban and institutional lawns. Additionally, suburban front yard lawns are adjacent to impervious surfaces and roads, potentially affecting exposure to atmospheric deposition from vehicles, and increasing the potential for compaction and low saturated infiltration rates next to high foot and vehicle traffic areas such as driveways (Online Resource 1).

The most marked difference between suburban front and backyards in this study was in soil $NO_3^-$ and soil $NH_4^+$. Several factors could contribute to the elevated $NO_3^-$ in the front yards including higher fertilizer use on front yards associated with the "public face function" of these areas (Locke et al. 2018a, b) and increased exposure to nitrogen deposition from vehicles due to their proximity to roads. Prior studies have found that nitrogen deposition from vehicles is greatest within 15 m from roadsides and is associated with higher soil $NO_3^-$ leaching than locations further from roadsides (Cape et al. 2004; Bettez et al. 2013; Redling et al. 2013). Our findings of higher $NO_3^-$ in front yards than backyards, suggests that atmospheric nitrogen deposition may be an important consideration in future investigations of N dynamics in residential lawns. The factors driving elevated soil $NH_4^+$ in backyards are not as clear, but one potential explanation is that pet use (and waste deposition) is plausibly higher in backyards (Hobbie et al. 2017). Other potentially important differences in landscape configuration between front and backyards may work to obscure topographic effects seen on larger parcel sizes, such as the distribution and type of trees, downspout placement, and shading effects from structures (Miles and Band 2015; Locke et al. 2018b). The potential effects of downspout placement and shading on soil moisture are discussed above and demonstrate how aspects of landscape configuration may be more important than fertilizer in overcoming the effects of topography in suburban lawns. However, these effects are speculative and warrant further investigation to disentangle which landscape gradients are important for driving patterns of N cycling in lawns.

## Nitrogen dynamics are variable and may generate hotspots of N mobilization

One key objective for this study was to determine if there are locations within lawns that have the *potential* to act as hotspots of N mobilization. To that end, we posit that how mobile or retentive N may be on a lawn is the result of an interaction between the capacity of the lawn to remove $NO_3^-$ via denitrification and to infiltrate water during storms thus preventing $NO_3^-$ from being mobilized in runoff. Previous research has suggested that lawns are generally retentive of N (Gold et al. 1990; Raciti et al. 2008), but it is not clear if lawns are uniformly retentive or if particular locations may be more or less susceptible to N mobilization or retention. We found that DNP and saturated infiltration rates varied both within and among lawns. This suggests that particular lawns within a neighborhood may be more likely to retain or mobilize N, and particular locations within an individual lawn may be more likely to retain or mobilize N. We found three distinct groupings in our study sites.

The first distinct grouping encompasses institutional lawns, which had both high DNP and high saturated infiltration rates suggesting these locations may be the most retentive of N of any of our study lawns across a range of rainfall and N source conditions, but also highlighting that institutional and residential lawns may not be functionally comparable. Institutional lawns are uniformly managed and far less utilized by people than typical residential lawns potentially increasing their capacity to remove N. The second grouping encompasses lawns in the exurban neighborhood which have generally low DNP and saturated infiltration rates, suggesting that these lawns may be more susceptible to mobilizing N during storm events as their capacity to retain water and process N are low. The final grouping encompasses suburban lawns that may be more variable in their N dynamics. These locations had high DNP but low saturated infiltration rates, suggesting these locations are likely to generate runoff during storms. However, whether these locations mobilize or remove N during a storm depends largely on whether the residence time of the water allows for $NO_3^-$ to be denitrified.

It is important to note that while a lawn may be susceptible to mobilizing N, how relevant that mobilization is to generating pollution downstream will depend on the juxtaposition of the lawn relative to impervious surfaces. For example, while exurban lawns may be more susceptible to mobilizing N than other lawn types, the longer hillslopes with longer flow paths in exurban lawns may present more opportunities for N processing than the short hillslopes in the suburban neighborhood. Additionally, the exurban neighborhood has fewer clear flow paths to impervious surfaces compared to the suburban neighborhood, essentially reducing the impact N mobilization from these lawns may have on downstream ecosystems. In contrast, the suburban front lawns have a suite of conditions including close proximity to impervious surfaces, short hillslopes, downspout inputs, and swales with low infiltration rates that make them more vulnerable to mobilizing N onto impervious surfaces. While this study has identified that particular locations have the *potential* to act as a hotspot of N mobilization, whether they function as such needs to be verified with actual field measurements of hydrologic and gaseous N flux.

### Carbon limitation of DNP may limit the capacity of urban lawns to retain N

Lawns have been shown to have the potential to accumulate organic matter (Pouyat et al. 2002; Golubiewski 2006) so it is notable that DNP in the study lawns were exclusively carbon limited. Lawn management could be one cause as lawn care can include the removal of wood, leaf litter and lawn clippings thus reducing carbon inputs into lawns (Peach et al. 2019). Additionally, high N inputs in urban lawns could result in a high demand for carbon, thus resulting in a depleted carbon pool (Waters et al. 2014). Drivers of carbon limitation in urban lawns warrant further investigation as results from this study suggest mitigation strategies that target increasing soil carbon may work to increase the capacity of lawns to retain N.

## Conclusions

The results of this study highlight several important avenues of investigation and the challenge of providing prescriptive mitigation strategies to reduce N mobilization from lawns. While we found that natural gradients, such as topography, affect the hydrobiogeochemistry of lawns, it appears that the configuration of the lawn may be as or more important when targeting lawns for N mitigation. The high *potential* but low risk for N mobilization onto impervious surfaces in the exurban lawns compared with the higher risk of N mobilization onto impervious surfaces in suburban front yard lawns highlights the need to better understand flow paths and N processing along these flow paths in lawns.

It is not clear from this study if fertilized lawns inherently act as hotspots of N mobilization. Direct measurements of N in runoff from these lawns are needed to make this assessment. However, fertilizer application does not appear to inherently increase or decrease the potential of a lawn to act as a hotspot of N mobilization. Rather, results from this study suggest that the lawns most at risk of N mobilization (suburban front yards) due to their proximity to impervious surfaces may have a complex suite of conditions increasing their vulnerability to N mobilization that may be challenging to mitigate. These conditions, such as N deposition, soil compaction adjacent to impervious surfaces, and downspout placements that increase runoff potential, would require mitigation strategies more tailored to individual lawns than just management of fertilizer inputs generally. Mitigation strategies, such as rain gardens, which focus on capturing and infiltrating excess runoff are potentially one way to address the multifaceted nature of these complexities.

The results here contribute to the emerging understanding of the structure, function, and environmental impacts of human-dominated landscapes, but also highlight the need for more research on lawns. Notably, this is a study of only 16 lawns in one city with a temperate climate. More research is needed to determine which results presented here are generalizable to other cities with different climates, underlying topography and mesotopography. Our analysis shows that while the landscape controls of water and N fluxes that have been well defined in "natural" landscapes are still important in urban landscapes, there are important interactions with human behaviors. In other words, biophysical characteristics do not overwhelm human behaviors nor do human behaviors overwhelm biophysical characteristics. Both matter and need to be considered to understand and manage the system. Analysis of these interactions increases our basic science understanding of "how urban landscapes work" and of how to improve the environmental performance of a dominant ecosystem and landscape type in the U.S.

**Acknowledgements** This work is part of a larger project seeking to understand coupled natural-human system dynamics of nitrogen in residential landscapes funded by the National Science Foundation CNH Grant (1615560). We would like to thank B. Glass-Siegel, D. Dillon, J. Mallinoff, A. Phillips, S. Jiang and N. Sonti for extensive help with field work. L. Martel provided invaluable support with laboratory analyses. Finally, we would like to extend our deepest thanks to the homeowners who graciously and enthusiastically volunteered their lawns for this study. The findings and conclusions in this publication are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy.

**Author contributions** Conceptualization: PMG, LEB, JMD, AJG, and JMG; Methodology: AKS, PMG, LEB, JMD and AJG; Formal analysis and investigation: AKS and LT; Writing—original draft preparation: AKS and PMG; Writing—review and editing: PMG, LEB, JMD, AJG, JMG, DHL, and LT; Funding acquisition: PMG, LEB, AJG, and JMG; Resources: PMG, LEB, and AJG; Supervision: AKS and PMG.

**Funding** This work was funded by the National Science Foundation Coupled Natural-Humans Systems Grant (1615560).

**Data availability** Data for the manuscript are available at the Environmental Data Initiative: https://doi.org/10.6073/pasta/67615100eabd2f3d43718759f85c131e

**Compliance with ethical standards**

**Conflicts of interest** The authors declare that they have no conflicts of interest.

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** All authors consent to publication of this manuscript.

## References

Amundson R, Jenny H (1997) On a state factor model of ecosystems. Bioscience 47:536–543. https://doi.org/10.2307/1313122

Baker LA, Hope D, Xu Y et al (2001) Nitrogen balance for the central Arizona-Phoenix (CAP) ecosystem. Ecosystems 4:582–602. https://doi.org/10.1007/s10021-001-0031-2

Band LE, Tague CL, Groffman P, Belt K (2001) Forest ecosystem processes at the watershed scale: hydrological and ecological controls of nitrogen export. Hydrol Process 15:2013–2028. https://doi.org/10.1002/hyp.253

Bettez ND, Marino R, Howarth RW, Davidson EA (2013) Roads as nitrogen deposition hot spots. Biogeochemistry 114:149–163. https://doi.org/10.1007/s10533-013-9847-z

Burke IC, Yonker CM, Parton WJ et al (1989) Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. Soil Sci Soc Am J 53:800–805. https://doi.org/10.2136/sssaj1989.03615995005300030029x

Burnham KP, Anderson DR (2004) Multimodel inference: understanding AIC and BIC in model selection. Sociol Methods Res 33:261–304. https://doi.org/10.1177/0049124104268644

Cadenasso M, Pickett S, Groffman P et al (2008) Exchanges across land-water-scape boundaries in urban systems. Ann N Y Acad Sci 1134:213–232. https://doi.org/10.1196/annals.1439.012

Cape JN, Tang YS, van Dijk N et al (2004) Concentrations of ammonia and nitrogen dioxide at roadside verges, and their contribution to nitrogen deposition. Environ Pollut 132:469–478. https://doi.org/10.1016/j.envpol.2004.05.009

Cleaves ET, Godfrey AE, Bricker OP (1970) Geochemical balance of a small watershed and its geomorphic implications. GSA Bull 81:3015–3032. https://doi.org/10.1130/0016-7606(1970)81[3015:GBOASW]2.0.CO;2

Cook EM, Hall SJ, Larson KL (2012) Residential landscapes as social-ecological systems: a synthesis of multi-scalar interactions between people and their home environment. Urban Ecosyst 15:19–52. https://doi.org/10.1007/s11252-011-0197-0

Creed IF, Beall FD (2009) Distributed topographic indicators for predicting nitrogen export from headwater catchments. Water Resour Res. https://doi.org/10.1029/2008WR007285

Duncan JM, Groffman PM, Band LE (2013) Towards closing the watershed nitrogen budget: spatial and temporal scaling of denitrification. J Geophys Res Biogeosci 118:1105–1119. https://doi.org/10.1002/jgrg.20090

Fissore C, Baker LA, Hobbie SE et al (2011) Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis-Saint Paul, Minnesota, urban region. Ecol Appl 21:619–639. https://doi.org/10.1890/10-0386.1

Fraser JC, Bazuin JT, Band LE, Grove JM (2013) Covenants, cohesion, and community: the effects of neighborhood governance on lawn fertilization. Landsc Urban Plan 115:30–38. https://doi.org/10.1016/j.landurbplan.2013.02.013

Gold AJ, DeRagon WR, Sullivan WM, Lemunyon JL (1990) Nitrate-nitrogen losses to groundwater from rural and suburban land uses. J Soil Water Conserv 45:305–310

Golubiewski NE (2006) Urbanization increases grassland carbon pools: effects of landscaping in Colorado's front range. Ecol Appl 16:555–571. https://doi.org/10.1890/1051-0761(2006)016[0555:UIGCPE]2.0.CO;2

Groffman PM, Grove JM, Polsky C et al (2016) Satisfaction, water and fertilizer use in the American residential macrosystem. Environ Res Lett 11:034004. https://doi.org/10.1088/1748-9326/11/3/034004

Groffman PM, Holland EA, Myrold DD et al (1999) Denitrification. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P (eds) Standard soil methods for long-term ecological research. Oxford University Press, New York

Groffman PM, Law NL, Belt KT et al (2004) Nitrogen fluxes and retention in urban watershed ecosystems. Ecosystems 7:393–403. https://doi.org/10.1007/s10021-003-0039-x

Groffman PM, Pouyat RV, Cadenasso ML et al (2006) Land use context and natural soil controls on plant community composition and soil nitrogen and carbon dynamics in urban and rural forests. For Ecol Manag 236:177–192. https://doi.org/10.1016/j.foreco.2006.09.002

Groffman PM, Williams CO, Pouyat RV et al (2009) Nitrate leaching and nitrous oxide flux in urban forests and grasslands. J Environ Qual 38:1848–1860. https://doi.org/10.2134/jeq2008.0521

Harrison XA, Donaldson L, Correa-Cano ME et al (2018) A brief introduction to mixed effects modelling and multi-model inference in ecology. PeerJ 6:e4794. https://doi.org/10.7717/peerj.4794

Hobbie SE, Finlay JC, Janke BD et al (2017) Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. Proc Natl Acad Sci 114:4177–4182. https://doi.org/10.1073/pnas.1618536114

Kaushal SS, Groffman PM, Band LE et al (2011) Tracking nonpoint source nitrogen pollution in human-impacted watersheds. Environ Sci Technol 45:8225–8232. https://doi.org/10.1021/es200779e

Kaye JP, Groffman PM, Grimm NB et al (2006) A distinct urban biogeochemistry? Trends Ecol Evol 21:192–199. https://doi.org/10.1016/j.tree.2005.12.006

Lagrosa J, Welty C (2017) GIS shapefile, spatial boundaries and land cover summaries for eight sub-watersheds of the baltimore ecosystem study LTER. Environ Data Initiat

Locke DH, Avolio M, Trammell TLE et al (2018a) A multi-city comparison of front and backyard differences in plant species diversity and nitrogen cycling in residential landscapes. Landsc Urban Plan 178:102–111. https://doi.org/10.1016/j.landurbplan.2018.05.030

Locke DH, Chowdhury RR, Grove JM et al (2018b) Social norms, yard care, and the difference between front and back yard management: examining the landscape mullets concept on urban residential lands. Soc Nat Resour 31:1169–1188. https://doi.org/10.1080/08941920.2018.1481549

Martinez NG, Bettez ND, Groffman PM (2014) Sources of variation in home lawn soil nitrogen dynamics. J Environ Qual 43:2146–2151. https://doi.org/10.2134/jeq2014.03.0103

Miles B, Band LE (2015) Green infrastructure stormwater management at the watershed scale: urban variable source area and watershed capacitance. Hydrol Process 29:2268–2274. https://doi.org/10.1002/hyp.10448

Milesi C, Running SW, Elvidge CD et al (2005) Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ Manage 36:426–438. https://doi.org/10.1007/s00267-004-0316-2

Ogden CB, van Es HM, Schindelbeck RR (1997) Miniature rain simulator for field measurement of soil infiltration. Soil Sci Soc Am J 61:1041–1043. https://doi.org/10.2136/sssaj1997.03615995006100040008x

Palta MM, Ehrenfeld JG, Groffman PM (2014) "Hotspots" and "hot moments" of denitrification in urban brownfield wetlands. Ecosystems 17:1121–1137. https://doi.org/10.1007/s10021-014-9778-0

Peach ME, Ogden LA, Mora EA, Friedland AJ (2019) Building houses and managing lawns could limit yard soil carbon for centuries. Carbon Balance Manag 14:9. https://doi.org/10.1186/s13021-019-0124-x

Petrovic AM (1990) The fate of nitrogenous fertilizers applied to turfgrass. J Environ Qual 19:1–14. https://doi.org/10.2134/jeq1990.00472425001900010001x

Pouyat R, Groffman P, Yesilonis I, Hernandez L (2002) Soil carbon pools and fluxes in urban ecosystems. Environ Pollut 116:S107–S118. https://doi.org/10.1016/S0269-7491(01)00263-9

Raciti SM, Groffman PM, Fahey TJ (2008) Nitrogen retention in urban lawns and forests. Ecol Appl 18:1615–1626. https://doi.org/10.1890/07-1062.1

Redling K, Elliott E, Bain D, Sherwell J (2013) Highway contributions to reactive nitrogen deposition: tracing the fate of vehicular NOx using stable isotopes and plant biomonitors. Biogeochemistry 116:261–274. https://doi.org/10.1007/s10533-013-9857-x

Reisinger AJ, Woytowitz E, Majcher E et al (2018) Changes in long-term water quality of Baltimore streams are associated with both gray and green infrastructure. Limnol Oceanogr 17:1–17. https://doi.org/10.1002/lno.10947

Reynolds WD, Elrick DE (1990) Ponded infiltration from a single ring: I. Analysis of steady flow. Soil Sci Soc Am J 54:1233–1241. https://doi.org/10.2136/sssaj1990.03615995005400050006x

Schimel D, Stillwell MA, Woodmansee RG (1985) Biogeochemistry of C, N, and P in a soil catena of the shortgrass steppe. Ecology 66:276–282. https://doi.org/10.2307/1941328

Spence PL, Osmond DL, Childres W et al (2012) Effects of lawn maintenance on nutrient losses via overland flow during natural rainfall events1. JAWRA J Am Water Resour Assoc 48:909–924. https://doi.org/10.1111/j.1752-1688.2012.00658.x

StataCorp (2019) Stata statistical software: release 16. StataCorp LP, College Station, TX

Suriyavirun N, Krichels AH, Kent AD, Yang WH (2019) Microtopographic differences in soil properties and microbial community composition at the field scale. Soil Biol Biochem 131:71–80. https://doi.org/10.1016/j.soilbio.2018.12.024

Tague C, Band L, Kenworthy S, Tenebaum D (2010) Plot- and watershed-scale soil moisture variability in a humid

Piedmont watershed. Water Resour Res. https://doi.org/10.1029/2009WR008078

Thompson GL, Kao-Kniffin J (2019) Urban grassland management implications for soil C and N dynamics: a microbial perspective. Front Ecol Evol. https://doi.org/10.3389/fevo.2019.00315

Vidon PG, Hill AR (2006) A landscape-based approach to estimate riparian hydrological and nitrate removal functions1. JAWRA J Am Water Resour Assoc 42:1099–1112. https://doi.org/10.1111/j.1752-1688.2006.tb04516.x

Walter MT, Walter MF, Brooks ES et al (2000) Hydrologically sensitive areas: variable source area hydrology implications for water quality risk assessment. J Soil Water Conserv 55:277–284

Waters ER, Morse JL, Bettez ND, Groffman PM (2014) Differential carbon and nitrogen controls of denitrification in riparian zones and streams along an urban to exurban gradient. J Environ Qual 43:955. https://doi.org/10.2134/jeq2013.12.0504

Wolman MG (1987) Sediment movement and knickpoint behavior in a small piedmont drainage basin. Geogr Ann Ser Phys Geogr 69:5–14. https://doi.org/10.1080/04353676.1987.11880192

Zhou W, Troy A (2008) An object-oriented approach for analysing and characterizing urban landscape at the parcel level. Int J Remote Sens 29:3119–3135. https://doi.org/10.1080/01431160701469065