SOIL CONDITIONS AND NITROGEN DYNAMICS IN URBAN GRASSLANDS

ELIZABETH H. DE LA REGUERA
Dickinson College, Carlisle, PA 17013 USA

MENTOR SCIENTIST: DR. PETER GROFFMAN
Cary Institute of Ecosystem Studies, Millbrook, NY 12545 USA

Abstract. Urban lawns often receive greater nitrogen inputs than natural systems and can have significant nitrogen losses to the environment. Nitrogen can be lost into the air in the form of nitrous oxide (N_2O) and into the water as nitrate (NO_3^-). Many lawns have compacted subsoil and thin layers of topsoil and there is concern that these “bad” lawns may not cycle nitrogen as efficiently and have significant hydrologic or gaseous loss. Within these lawns, the compacted subsoil may be acting as an impervious surface leading to water and nitrogen ponding between the sod and subsoil, which stimulates gaseous losses. This study sought to determine if lawns with compacted subsoil support higher rates of hydrologic and/or gaseous nitrogen losses than lawns with more “natural” soil profiles. Denitrification potential along with other related variables were measured in plots that received a subsoiling and compost addition treatment to remediate compacted subsoil, unremediated “reference” plots, swales (low spots) located between treatment plots, and from a “good” reference plot. Denitrification potential was highest in the swales compared to the reference, compost, and unremediated plot. The composted site had the lowest nitrate pool and nitrification rate, along with negative mineralization rate. The data suggests that there is microbial immobilization (retention) taking place in the composted site (microbes are converting inorganic N into organic N). The unremediated plot and swales had more denitrification, suggesting that compaction on these “bad” lawns may be preventing hydrologic losses of nitrogen by facilitating gaseous losses.

INTRODUCTION

Between 1982 and 1997, the extent of urbanized land has increased 47% in the United States (Fulton et al., 2001). One of the most obvious components of urbanized land is turfgrass lawns. These areas often receive greater nitrogen inputs than natural systems (Groffman et al., 2009) and can have significant nitrogen losses to the environment, especially when overwatered and overfertilized (Raciti et al. 2011). Nitrogen can be lost into the air in the form of nitrous oxide (N_2O), which has a global warming potential that is 298 times greater than CO_2 on a 100 year timescale (Townsend-Small et al. 2011). Nitrogen can be lost to the water as nitrate, which is a drinking water pollutant and causes eutrophication in coastal waters.

At the National Science Foundation funded Baltimore urban Long-Term Ecological Research (LTER) site, nitrogen inputs, outputs and transformations in residential ecosystems have been measured with a specific focus on lawns. In a ^{15}N-tracer study, it was found that a pulse of nitrate (NO_3^-) was quickly incorporated or retained in soil organic matter, fine roots, aboveground vegetation biomass, microbial biomass, and thatch in Baltimore area lawns (Raciti et al., 2008). In the short-term, these lawns immobilized nitrogen in mineral soil organic matter (SOM), which was then followed by rapid uptake and incorporation into plant and microbial biomass (Raciti et al., 2008). This suggests that N is tightly cycled in residential lawns, which may contribute to high rates of retention that minimize losses to the environment (Groffman et al. 2009).

All of these Baltimore LTER lawn studies were done on sites with deep relatively undisturbed soil profiles that maximize the potential for nitrogen cycling and retention (“good” lawns). These studies have not included sites with compacted subsoil, and thin layers of topsoil. There is great concern that these “bad” lawns may not cycle nitrogen as efficiently and have significant hydrologic or gaseous loss. There are two significant functional differences that could be occurring in these lawns: 1) The compacted subsoil acts as an impervious surface and leads to water and nitrogen ponding between the sod and subsoil that creates an anaerobic environment. Such a change would lead to high rates of denitrification, an anaerobic microbial process that converts reactive nitrogen into nitrogen gases. 2) Instead of ponding, if the water and nitrogen are unable to penetrate the subsoil, they may instead run-off or leach, resulting in a significant hydrologic loss (Figure 1). If water runs off, it may pond in low spots (swales) adjacent to lawns. These swales may function as anaerobic hotpots of denitrification.

The objective of this study was to determine if lawns with compacted subsoil support higher rates of hydrologic and/or gaseous nitrogen losses than lawns with more “natural” soil profiles. To address this objective, we measured a series of variables that are indicative of the potential for nitrogen loss or retention. We hypothesize that:

(a) If there is nitrogen and water ponding in “bad lawns”, there will be a significantly higher amount of denitrification occurring.
(b) Soils with ponding will have significantly lower pools of soil nitrate available for hydrologic loss.
(c) Microbial and root biomass will be lower in “bad lawns” limiting the potential for plant and microbial uptake of nitrogen.
(d) Ponding may occur vertically in the soil profile and/or horizontally within low spots (swales).

METHODS

Sampling Sites

Six site locations were chosen on the University of Maryland Baltimore County (UMBC) campus in Baltimore County, MD USA (39°15’17.31N, 76°42’08.71”W). We sampled 9 plots located adjacent to the Technology Resource Center (TRC) where turf had developed over highly disturbed, compacted material. Three of these plots had received a subsoiling and compost addition treatment to remediate compacted subsoil and facilitate turf development. We also sampled three unremediated “reference” areas adjacent to these plots as well as three swales located in between the treatment plots. These swales were narrow, drainage channels that had developed between the treatment plots that were obviously wet after a large rainfall event. Six other samples were taken at and athletic field (Shelbourne), also located on the UMBC campus. We took three samples from the highly compacted field itself and three samples from wet drainage swales located at the edge of the field. Finally, we took three samples from one of the BES grass long-term study plots on the UMBC campus. This plot contains turf developed over a natural soil profile. A total of 18 plots were sample (9 at TRC, 6 at Shelbourne Field, and 3 at the BES long-term study plot).

Analytical Methods

An Environmental Service Products 1 meter soil corer was used to take 30cm deep cores at each site. The cores were encased in plastic tubes that were kept refrigerated until needed. 0-10 cm of the core was separated and placed into a Ziploc bag. The remaining 10-30 cm was also put into a Ziploc bag.

Rocks and roots were separated from the soil, cleaned, and weighed after dried. Soil moisture content was determined by drying a sample of soil at 60°C for 48 hours. Soil organic matter was determined by loss of ignition at 450°C for 4 hours. The amount of inorganic nitrogen (NO_3^- and NH_4^+) in soil was determined by an extraction with 2M KCl.

Denitrification enzyme activity (DEA) was measured with a modified short-term anaerobic assay developed by Smith and Tiedje (1979) as described by Groffman et al. (1999). Microbial biomass C and N content was measured with the chloroform fumigation-incubation method (Jenkinson and Powlson, 1976). Potential net N mineralization and nitrification and microbial respiration were measured in a 10-day incubation of field moist soils in the laboratory. Potential net N mineralization was calculated from the accumulation of inorganic N (NH_4^+ and NO_3^-), potential net nitrification was calculated from the accumulation of NO_3^-, and microbial respiration was calculated from the accumulation of CO_2 over the 10-day incubation.

Statistical Analysis

Differences between the six “treatments” (TRC compacted lawn, TRC remediated compacted lawn, TRC drainage swale, Shelbourne compacted lawn, Shelbourne drainage swale, LTER reference plot) were evaluated with one-way analysis of variance. Specific differences between treatments were determined with a Duncans post-hoc multiple comparisons test. Relationships between variables were explored with parametric (Pearson) and non-parametric (Spearman) correlation analysis. All analyses were done with the Statistical Analysis System (SAS Institute Inc., Cary, North Carolina, USA 9.2).

RESULTS

The 18 plots sampled were broken up into 4 subcategories: swales (TRC and Shelbourne), reference (LTER), compacted (Shelbourne field and TRC unremediated), and remediated with compost (TRC).

Soil organic matter content at 0-10cm depth was significantly higher ($p < 0.10$) at the reference site (0.50 ± 0.02 g/kg) than at the compacted sites (0.31 ± 0.05 g/kg). The compost and swale sites had intermediate levels of organic matter (Figure 2). There was no significant difference in organic matter between treatments at 10-30cm and small variation (0.25 - 0.32 g/kg).

DEA at 0-10cm ranged from 15.4 to 68.2 ng N/g soil/hr, with the swale having the highest and the compost mediated having the lowest DEA (Figure 3), but there were no significant differences between treatments. At 10-30cm, DEA was significantly ($p < 0.05$) lower and ranged from 0.95 to 5.78 ng N/g soil/hr. DEA per unit of microbial biomass C showed the same patterns and lack of statistically significant differences as DEA, ranging from 0.03 (reference) to 0.25 (compost) at 0 – 10cm and from 0.01 (swale) to 0.04 (compacted) at 10 – 30cm (Figure 4). The reference site had the highest and the compost had the lowest nitrate pool and nitrification rates ($p < 0.10$). Nitrate pools at 0 – 10cm ranged from 0.50 (compost) to 4.3 (reference) ug N/g dry soil (Figure 5). Nitrification rates at the same depth ranged from -0.05 (compost) to 0.88 (reference) ug N/g dry soil/day. Nitrate pools and nitrification rates were lower and showed less differences at 10 – 30cm, but the patterns were similar (Figure 6). The reference site had the greatest nitrate pool (1.90 ug N/g dry soil) and the compost site had the smallest (0.19 ug N/g dry soil). The reference site also had the highest rate of nitrification at 10 - 30cm (0.13 ug N/g dry soil/day) while compost still had the lowest rate (-0.009 ug N/g dry soil/day).

The mass of roots at 0 – 10cm did not vary among treatments and ranged from 0.24 (reference) to 0.66 (swale) g/kg (Figure 7). At 10-30cm, root biomass was lower, with no significant difference between treatments and ranged from 0.045 to 0.12 g/kg. Potential net N mineralization showed similar patterns as nitrification, with particularly low ($p < 0.10$) values in the compost treatment (-0.14) and highest values in the reference (0.69) ug N/g dry soil/day (Figure 8). Patterns were less marked at 10 – 30cm, but the compost treatment still had the lowest ($p < 0.10$) net N mineralization rate (-0.13 ug N/g dry soil/day).

DISCUSSION

Previous research in the Baltimore Ecosystem Study suggested that N is tightly cycled in residential lawns, with active cycling of nitrogen between soils and plants (Raciti et al. 2008) which may contribute to high rates of retention that minimize losses to the environment (Groffman et al. 2009). These studies found that the vast majority of lawns had relatively intact soil profiles, with little evidence of compaction and/or alteration of soil parent materials (Raciti et al. 2011a). The present study was driven by the idea that compacted and disturbed sites ("bad lawns") were more common than these previous studies suggest and their nitrogen cycling and retention might be much less efficient than in the previously studied "good lawns".

Mechanistically, we hypothesized that within the "bad" lawns, compacted subsoil was acting as an impervious layer leading to ponding of water in the soil profile. The fate of this ponded water is unclear and important. It could create an anaerobic condition that leads to denitrification, or it could lead to runoff or leaching. If there is leaching or runoff or denitrification taking place, there is not much available nitrogen left for plant uptake, which we believed would cause a decline in plant "health", resulting in fewer roots and microbes. With less healthy microbes, roots, and plants, there would be little retention of nitrogen and a "looser" nitrogen cycle.

Ponding is typically a vertical occurrence, which is what we had expected to find in the compacted lawns. While in the field, we noticed our feet sinking into the ground because it had rained the night before. There was part of the landscape that had visible surface pooling of water. This surface ponding indicated that there was most likely horizontal ponding of runoff into the low spots, i.e. swales. We had originally hypothesized that: a) there would be greater denitrification in compacted lawns and soils with ponding, b) there would be lower soil nitrate pools in compacted lawns and soils with ponding, c) microbial and root biomass would be lower in compacted lawns. After observing surface ponding, we added another hypothesis; d) ponding may occur vertically or horizontally in low spots (swales).

Our data supports our original hypothesis (d) that there is greater denitrification potential in swales. The swale soils had the highest denitrification because they were wet due to their low position adjacent to unremediated grass plots that produce surface runoff. Wet soils have less oxygen, which stimulates denitrification, an anaerobic process. This result is consistent with Raciti et al. (2011) who found that "under wet or saturated conditions, soils amended with fertilizer or NO_3^- had high N_2 fluxes". Swales may therefore be important denitrification "hotspots" in the landscape. If we construct swales surrounding a landscape that receives high amounts of nitrogen, it's possible they can help to decrease leaching and promote more gaseous losses. Further study into swales and the landscapes they are near may help in understanding how efficient swales can be in managing nitrogen water pollution problems.

Somewhat surprisingly, we saw no evidence for denitrification in unremediated lawns with compacted subsoils (hypothesis a), i.e., the reference site had higher DEA than the unremediated plots. The reference plot was likely higher than the unremediated plots because there was more organic matter in the reference plot, which acts as an electron donor, stimulating denitrification. These findings also suggest that the compaction may prevent infiltration but it does not lead to enough vertical ponding to create anaerobic conditions necessary for denitrification. However, horizontal ponding in the swales appears to facilitate denitrification.

We expected to see low nitrate in swales (hypothesis b), which is supported by our data. Three factors that impact nitrate pools are 1) the production of nitrate by nitrification and consumption by 2) denitrification and 3) immobilization. The swales likely had less nitrate due to high rates of denitrification while the unremediated plot likely had low nitrate due to low rates of nitrification.

The compost plots likely had low nitrate due to high microbial immobilization; i.e., microbes converted inorganic N into organic N due to the high amounts of organic matter found in the composted site. The way in which the compost plots were created by Stu Schwartz (UMBC- BES) were by digging down in the unremediated plots to where the compaction ended, the compacted subsoil was tilled, compost was added, and then spading took place in order to circulate both the now uncompacted subsoil and the compost. The addition of compost appears to create a healthier lawn with higher microbial biomass and tighter nitrogen cycling. It's possible, through further research, that the lawns remediated with compost may be healthier than "standard" reference plots.

The mass of roots measured did not support the hypothesis that there would be fewer roots in unremediated lawns (hypothesis c). Root biomass is controlled by production and decomposition, both of which likely influenced our results. Surprisingly, the swales and unremediated lawns had the highest (but not significant) root biomass, meaning that there was either higher production and/or slower decomposition of roots compared to the compost and reference sites. If plants or grass are not getting enough water or nutrients from the soil, they'll invest more energy into root production. With high root biomass and low nitrate pools, it's possible the roots in the compacted sites and swales are taking up the nitrate. Raciti et al. (2008) found that "significant amounts of ^{15}N were recovered in fine roots", which were generally higher in lawns than forests. Soils at the unremediated and swale sites were compacted and it is quite possible that plants were stressed at these sites. We also noted significant amounts of roots in the compacted layers of soil at these sites and it is also quite possible that decomposition of these roots was inhibited by the compacted soil conditions.

Results from this study significantly increase our understanding of nitrogen dynamics in lawns with compacted subsoil. Compacted subsoils affect the movement of water in and through soil profiles. Our results suggest that vertical ponding within the soil profile does not create anaerobic conditions necessary for denitrification but rather results in lateral runoff. If this runoff flows into low spots (swales), it can create denitrification hot spots, which could prevent the movement of nitrogen into surface waters, a surprisingly positive aspect of these "bad lawns".

Lawns remediated with compost are more beneficial than we had originally thought. The addition of compost, which has a high carbon content, results in a "tightening" of the nitrogen cycle. Tight nitrogen cycling helps in reducing the loss of nitrogen through hydrologic and/or gaseous losses.

Our findings suggest that residential landscapes need to be thought of in three, rather than two dimensions. It is important to recognize that water, might be running off horizontally from the compacted lawns, and may move into low spots (swales) with high denitrification potential. Runoff always creates a potential for surface water pollution. However, flowing through swales may help to decrease hydrologic nitrogen loss.

Understanding where swales are typically located i.e., between residential lawns, near streams, etc, is something that should be documented to see just how common they are. If more studies also show that swales are denitrification hot spots that mediate hydrologic loss from surrounding landscapes, perhaps more landscapes should include swales. Deliberate placement of swales within landscapes could help with the global nitrogen problem of hydrologic loss into waterways.

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APPENDIX

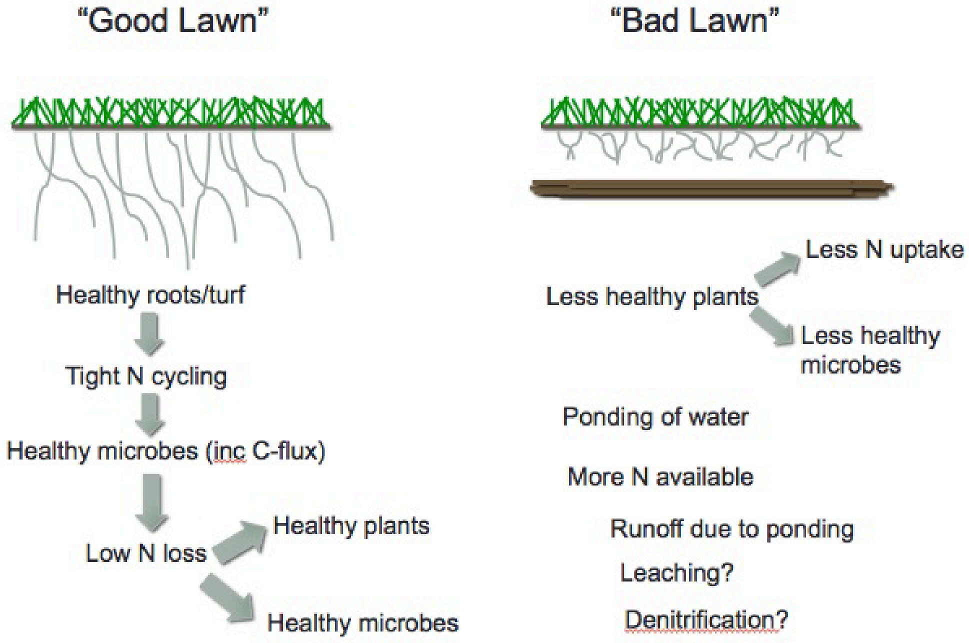

FIGURE 1. Schematic of a "good lawn" versus a "bad lawn".

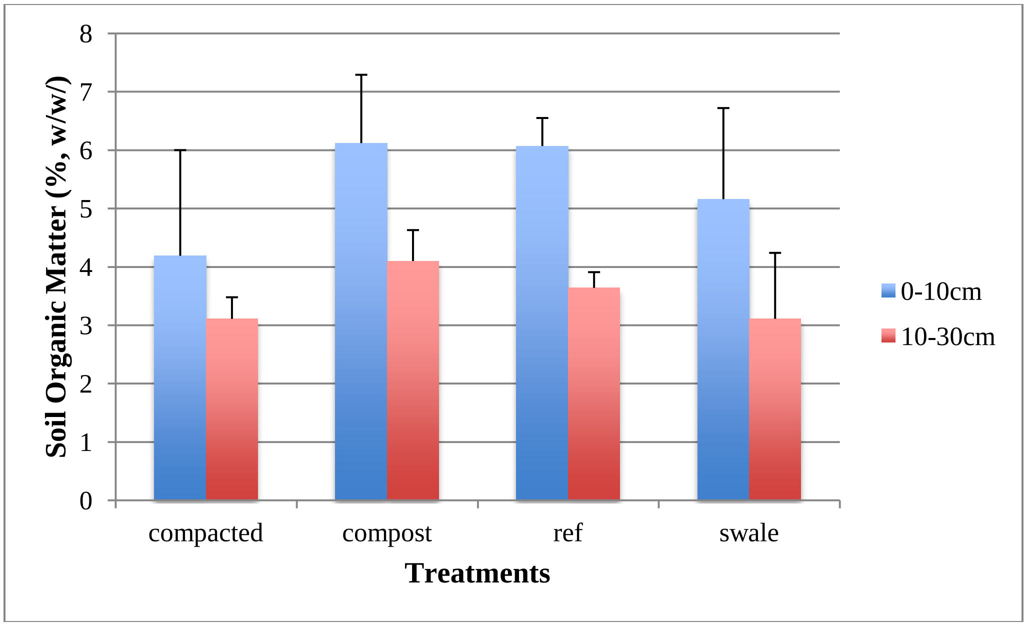

FIGURE 2. Soil organic matter in healthy (ref), compost treated, swale, and unremediated (compacted) lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard deviation) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites split into 0 – 10cm and 10 – 30cm depths.

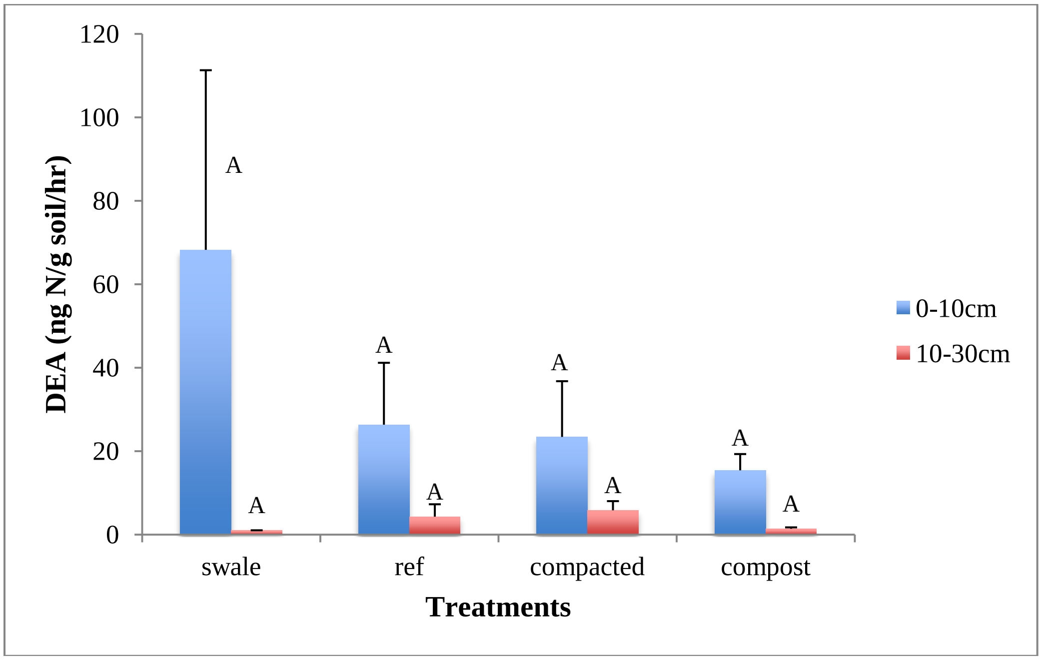

FIGURE 3. Denitrification enzyme activity in swale, healthy (ref), unremediated (compacted), and compost treated lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard error) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites split into 0 – 10cm and 10 – 30cm depths.

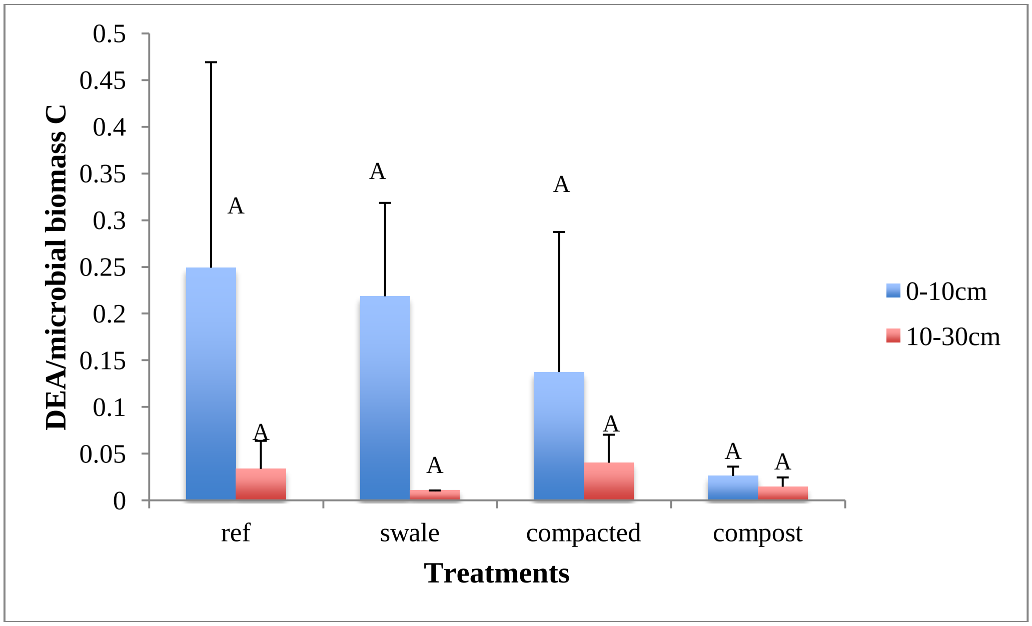

FIGURE 4. Mean denitrification enzyme activity per microbial biomass carbon in swale, healthy (ref), unremediated (compacted), and compost treated lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard error) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites split into 0 – 10cm and 10 – 30cm depths.

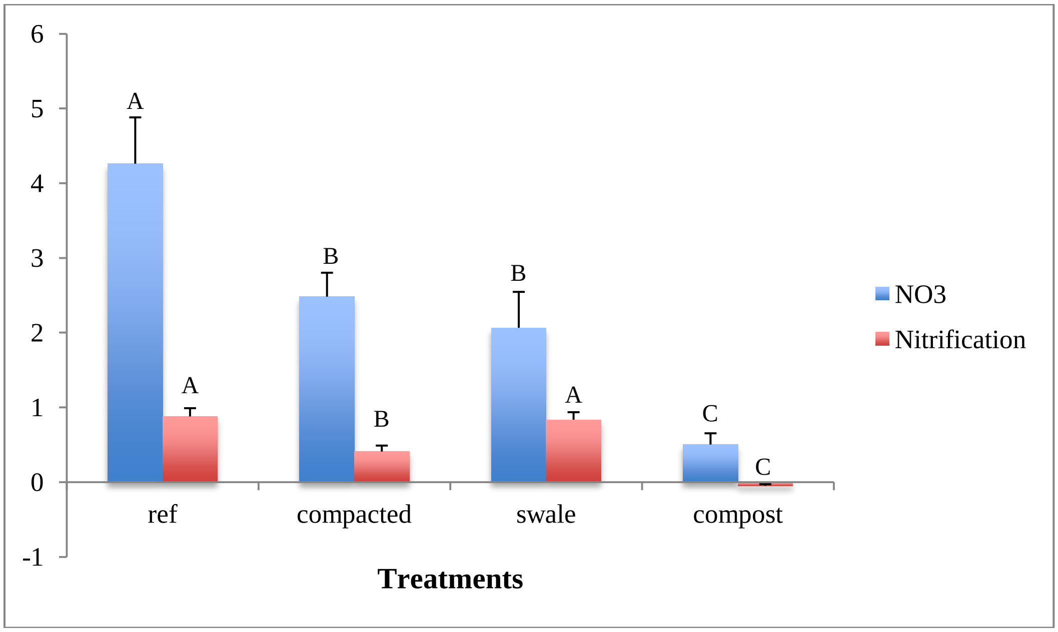

FIGURE 5. Soil nitrate pool (ug N/g dry soil) and potential net nitrification rates (ug N/g dry soil/day) at 0 – 10cm depth in healthy (ref), unremediated (compacted), swale, and compost treated lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard error) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites.

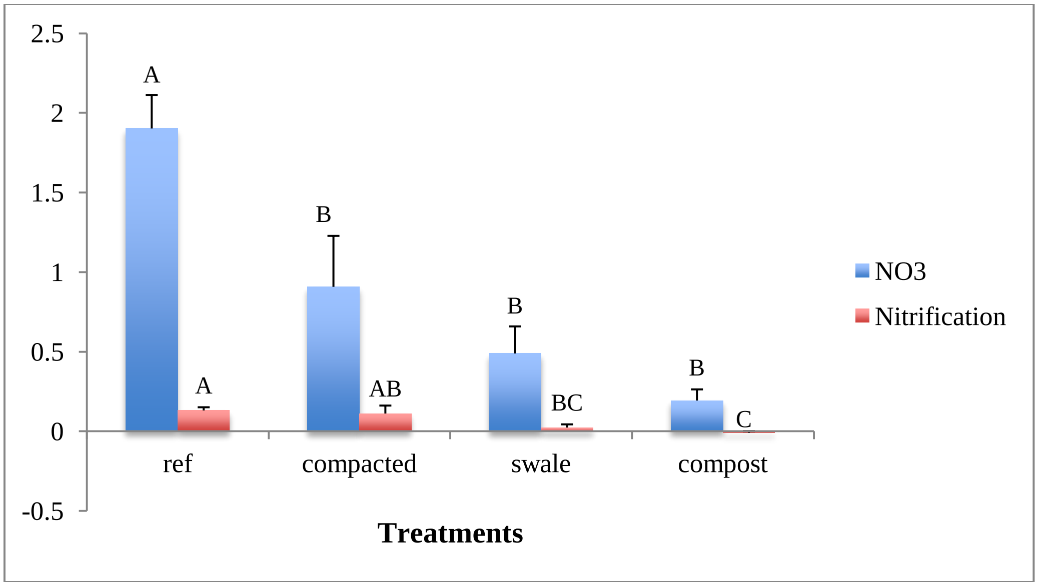

FIGURE 6. Soil nitrate pool (ug N/g dry soil) and potential net nitrification rates (ug N/g dry soil/day) at 10 – 30cm depth in healthy (ref), unremediated (compacted), swale, and compost treated lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard error) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites.

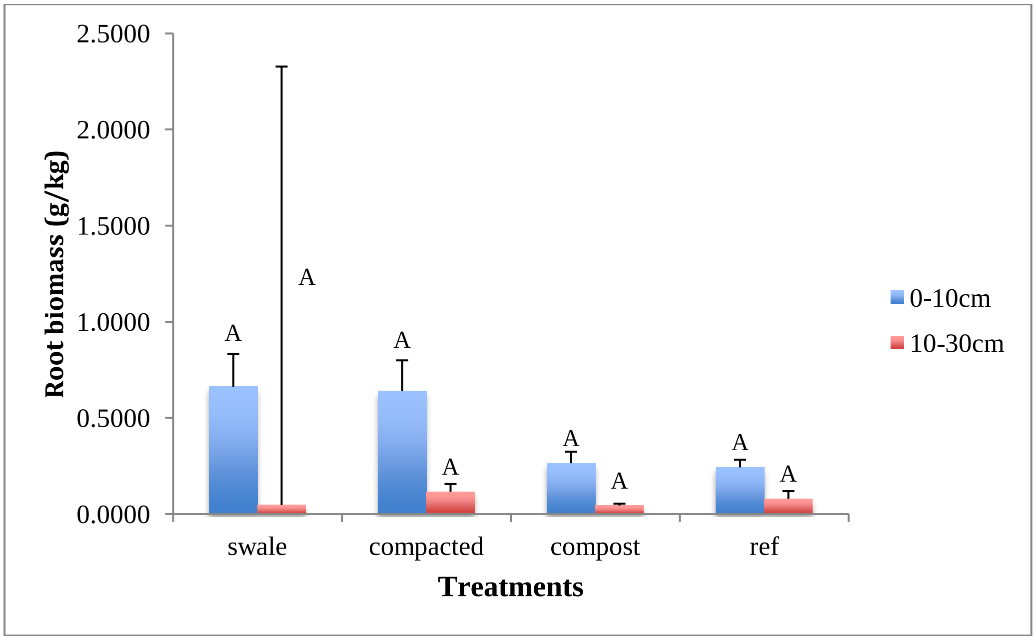

FIGURE 7. Root biomass (g/kg) in swale, unremediated (compacted), compost treated, and healthy (ref) lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard error) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites split into 0 – 10cm and 10 – 30cm depths.

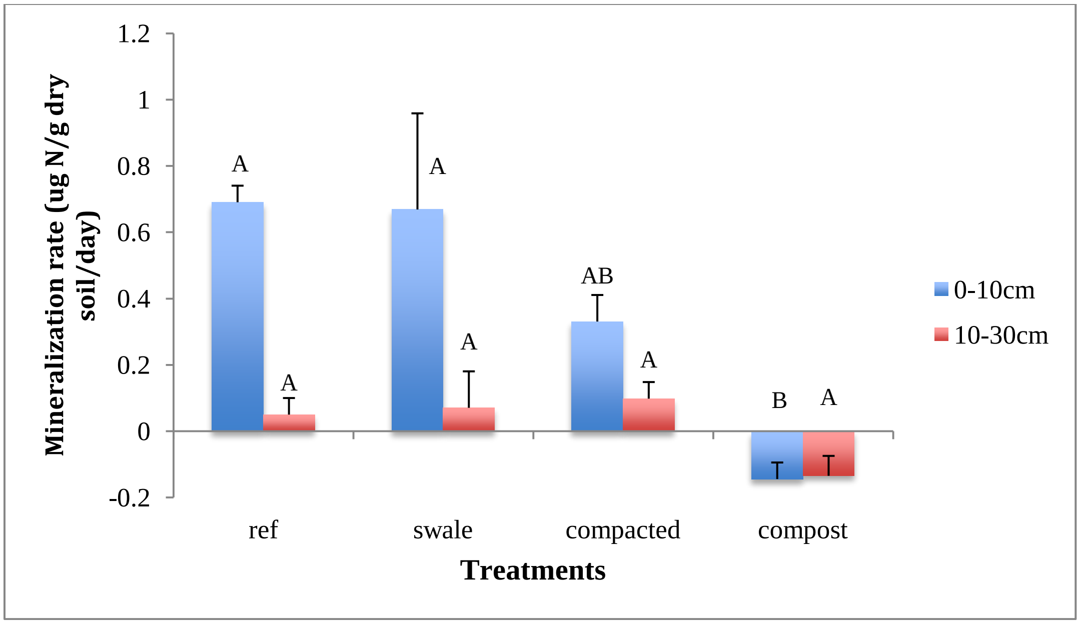

FIGURE 8. Potential net N mineralization rate in healthy (ref), swale, unremediated (compacted, and compost treated lawns in Baltimore, MD, sampled in June 2013. Values are mean (with standard error) of three samples taken at one reference site, one compost treated site, two swale sites, and two compacted sites split into 0 – 10cm and 10 – 30 cm depths.