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Carbon sequestration and greenhouse gas emissions in urban turf

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[1] Undisturbed grasslands can sequester significant quantities of organic carbon (OC) in soils. Irrigation and fertilization enhance CO_2 sequestration in managed turfgrass ecosystems but can also increase emissions of CO_2 and other greenhouse gases (GHGs). To better understand the GHG balance of urban turf, we measured OC sequestration rates and emission of N_2O (a GHG $\sim$ 300 times more effective than CO_2) in Southern California, USA. We also estimated CO_2 emissions generated by fuel combustion, fertilizer production, and irrigation. We show that turf emits significant quantities of N_2O (0.1–0.3 g N m^{-2} yr^{-1}) associated with frequent fertilization. In ornamental lawns this is offset by OC sequestration (140 g C m^{-2} yr^{-1}), while in athletic fields, there is no OC sequestration because of frequent surface restoration. Large indirect emissions of CO_2 associated with turfgrass management make it clear that OC sequestration by turfgrass cannot mitigate GHG emissions in cities. **Citation:** Townsend-Small, A., and C. I. Czimczik (2010), Carbon sequestration and greenhouse gas emissions in urban turf, *Geophys. Res. Lett.*, *37*, L02707, doi:10.1029/2009GL041675.

1. Introduction

[2] Photosynthetic uptake of atmospheric carbon dioxide (CO_2) can be accompanied by longer-term storage of organic carbon (OC) in soils in undisturbed grasslands [*Matson et al.*, 1997; *McLauchlan*, 2006]. In managed turfgrass systems, irrigation and fertilization enhance plant productivity and OC storage, but can also increase soil emissions of other greenhouse gases (GHGs), including nitrous oxide (N_2O) [*Kaye et al.*, 2004]. Management processes also consume energy and emit CO_2 [*Schlesinger*, 1999; *Lal*, 2004]. Turfgrass is a common element of urban areas, and its extent is increasing [*Robbins and Birkenholtz*, 2003]. Currently, turfgrass covers 1.9% of land in the continental U.S., making it the most common irrigated crop [*Milesi et al.*, 2005]. Urban soils have high OC densities [*Pouyat et al.*, 2009; *Churkina et al.*, 2009], but other aspects of their biogeochemistry are unknown [*Pataki et al.*, 2006].

[3] Of particular concern for turf biogeochemistry is fertilization, the main driver of increasing atmospheric N_2O (global warming potential (GWP) 298 x CO_2) [*Forster et al.*, 2007]. Because of high spatial and temporal variability, the global N_2O budget has large uncertainties [*Forster et al.*, 2007]. In agricultural soils, fertilizer-derived N_2O emissions can overcompensate for CO_2 uptake by plants and storage in soils, resulting in a positive contribution to global warming [*Matson et al.*, 1997; *Robertson et al.*, 2000]. Previous studies of turfgrass have either focused on quantifying OC sequestration rates [*Milesi et al.*, 2005; *Pouyat et al.*, 2009] or N_2O emissions [*Guilbault and Matthias*, 1998; *Kaye et al.*, 2004; *Bijoor et al.*, 2008; *Hall et al.*, 2008]. Lacking in previous efforts is a determination of the balance between OC storage and GHG emissions, crucial for proper understanding of potential carbon sinks. In order to estimate the net GWP of urban turf, we measured OC sequestration rates and N_2O emissions in ornamental lawns and athletic fields in four parks in Southern California, USA. We also estimated indirect CO_2 emissions from fuel consumption, fertilization, and irrigation.

2. Site Description and Methods

[4] The study was conducted in four parks located within a 7 km radius in Irvine, CA, USA (33°41′N, 117°47′W; average annual temperature $\sim$19°C; rainfall $\sim$350 mm yr^{-1}). Previous to 1970, the area was under agriculture for 100+ years. Soils are loamy and formed from moderately alkaline and calcareous parent material (more detail in Table S1 of the auxiliary material) [U.S. Department of Agriculture, 1978].[2] From surveys of remnant un-urbanized land, we know that these soils have very low (<1%) OC contents. The parks in the current study were established between 1975 and 2006. We assumed the parks represented a chronosequence of OC accumulation since urbanization. As with any chronosequence study, we cannot fully exclude differences in initial soil properties, but these are likely to be minor due to the close proximity of the parks to each other and because soils are scraped to bedrock before park development. Each park contains two turf types: athletic fields (soccer and baseball) and ornamental lawns. Grass is trimmed and mulched weekly, and watered regularly with recycled wastewater based on local estimates of evapotranspiration: soils consistently had high soil moisture (20–50% of pore space).

[5] To assess OC sequestration, we sampled 8–12 cores to 20 cm depth in each park and each treatment every 10 m in linear transects. The number of samples taken in each turf type reflects the relative area covered by each type. Samples were dried at 60°C, weighed, and sieved to remove rocks >2 mm. Soil bulk density was measured on every sample and corrected for the mass of particles >2 mm. A sub-sample was ground to powder and acidified with 2M HCl for 24 hrs to remove carbonates. Total OC and nitrogen contents were quantified with an elemental analyzer (EA), and stocks were calculated using EA data and bulk density.

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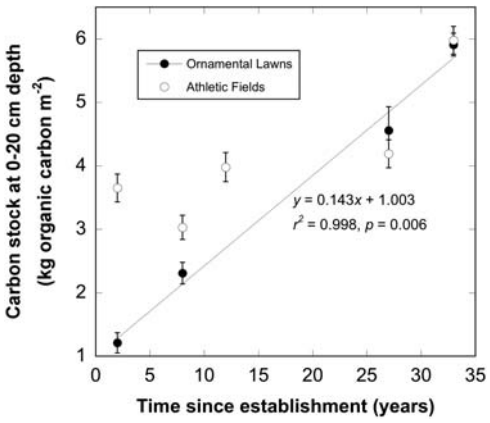

Figure 1. Organic carbon (OC) in the top 20 cm of soil in ornamental lawns and athletic fields established within 2 and 33 years (average ± SE). There is a significant linear relationship between OC stock and lawn age in ornamental lawns (filled circles), corresponding to accumulation rate of 0.14 kg OC m^{-2} yr^{-1}.

[6] N_2O fluxes in each type of turf were quantified using 3 static chambers (~25 cm diameter) randomly placed atop of turf [*Bijoor et al.*, 2008]. Chambers were kept atop turf for 28 minutes with air samples withdrawn through the top of the chamber at 7 min intervals starting at time = 0. Samples were withdrawn in 30 mL nylon syringes with plastic stopcocks and immediately transferred to pre-evacuated glass vials crimped with gray butyl rubber septa. Samples were analyzed within 24 hrs on a gas chromatograph with electron capture detector with N_2O standards bracketing expected concentrations. Fluxes were calculated from the slope of the line of N_2O concentration in each chamber vs. time. Regressions with $r^2 < 0.9$ were assumed to represent nil fluxes.

[7] To estimate background fluxes of N_2O, we sampled both types of turf in each of the four parks approximately once per month for one year (May 2008–2009), usually on separate days for each park. Over the entire experimental period, there was no significant difference in N_2O emissions between parks ($p < 0.05$) or turf type ($p < 0.05$), so baseline N_2O fluxes were calculated as the average of all of the flux measurements (3–12 chambers) from each measurement day. We also sampled N_2O flux at an increased frequency during fertilization periods. A total of five fertilizer events were followed in both turf types, and we sampled daily starting one or two days prior to fertilization and continuing until fluxes returned to baseline levels (about 8 days). Fertilizers included sulfur-coated urea, calcium nitrate, Nitra King (19-4-4), and Turf Supreme (16-6-8). In parallel with N_2O fluxes, we measured air and soil temperature and soil moisture (at 5 cm).

[8] Global warming potential (in CO_2 equivalents; g CO_2 m^{-2} y^{-1}) is calculated as by *Robertson et al.* [2000]. The accumulation rate of OC in ornamental lawns (in g C m^{-2} yr^{-1}) is derived from the slope of the regression line of carbon stock versus time in Figure 1. Processes that result in a net uptake of CO_2 or CO_2-equivalents are denoted with a negative sign; and vice versa. Significant differences between soil OC and N_2O emissions from the different parks and treatments in the study were assessed using a two-tailed t-test for comparing between two groups, and ANOVA for three or more groups. Tables of significance of the regression coefficient r were used to assess significance of linear correlations.

3. Results and Discussion

[9] A comparison of OC stocks in ornamental lawns with athletic fields along the chronosequence reveals striking differences in OC cycling (Figure 1). Ornamental lawns had low initial OC stocks (1.2 kg C m^{-2} for the top 20 cm of soil), but sequestered OC at a rate averaging 0.14 kg C m^{-2} yr^{-1}. In contrast, athletic fields had higher initial OC contents (~3.5 kg C m^{-2}) but no consistent trend in OC content over the study period, although the oldest athletic field did have significantly more OC than the other fields ($p < 0.0001$) (Figure 1). The difference in initial conditions can be attributed to the establishment method for the different turf types, as lawns and athletic fields at each point in Figure 1 are located in the same park and on the same parent material. Ornamental lawns are established from seed on existing soil. Athletic fields are constructed from imported turfgrass sods that add allochthonous OC to the system, then are renovated extensively every year, including tilling and re-sodding to replace dead grass, and frequent aeration to offset compaction, similar to practices employed in conventional agriculture which disrupt soil OC accumulation [*Matson et al.*, 1997; *McLauchlan* 2006]. Athletic field sod may have sequestered OC on the turf farm, but these fields do not store OC *in situ* until 30+ years after establishment.

[10] In the ornamental lawns in the current study, which are not subject to intense physical perturbations, the high productivity of the perennial vegetation overwhelms pre-existing differences between parks in soil type, density, and initial OC content, resulting in significant storage of OC in soils. These high OC stocks are typical for ornamental lawns, which have the highest OC density of urban soils and can accumulate OC rapidly [*Pouyat et al.*, 2009]. OC accumulation in ornamental lawns in the current study is close to that observed in re-growing forests in the north-eastern USA [*Barford et al.*, 2001]. In contrast to OC, we found no significant accumulation of N in soils over time (ornamental lawns: $y = 0.01x + 0.17$, $r^2 = 0.85$, $p = 0.08$; athletic fields: $y = 0.008x + 0.26$, $r^2 = 0.57$, $p = 0.14$) (Table S1). Total N in soils was 0.35 ± 0.2 kg N m^{-2} in ornamental lawns and 0.40 ± 0.1 kg N m^{-2} in athletic fields (mean ± SD) (Table S1).

[11] Besides the obvious ability of undisturbed lawns to sequester atmospheric CO_2, other factors contribute to the overall GWP of lawns. Several previous studies have shown that urban turfgrass emits N_2O after fertilization and/or irrigation [*Guilbault and Matthias*, 1998; *Kaye et al.*, 2004; *Bijoor et al.*, 2008; *Hall et al.*, 2008]. The turf in the current study was a source of N_2O throughout most of the year. Some past studies have used relationships between N_2O emissions and soil moisture, temperature and/or soil OC content to model annual fluxes of N_2O [*Scanlon and Kiely*, 2003; *Flechard et al.*, 2007]. Here, however, soil moisture and temperature were relatively constant, and the main driver of N_2O emissions was time since fertilizer

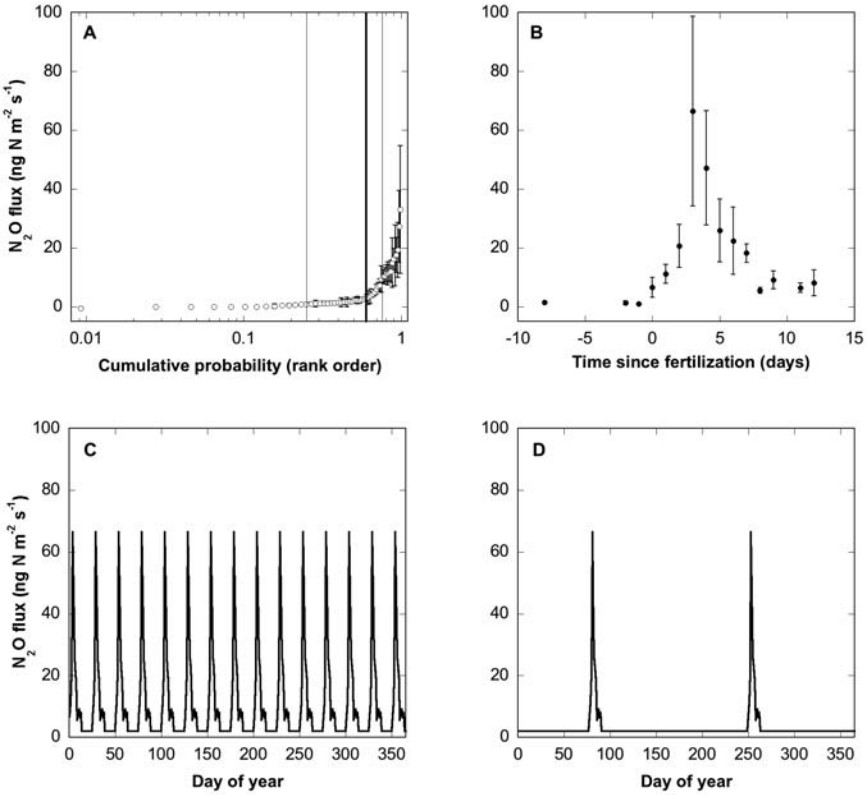

Figure 2. (a) Background N_2O fluxes from ornamental lawns and athletic fields (average of 3–12 measurements ± SE), organized in ascending order such that a normally distributed dataset would fall along a straight line. Data are from two weeks or more after fertilization. The median N_2O flux was 2.0 ng N m^{-2} s^{-1} (dark line) with 50% of the values falling between 0.8 and 9.3 ng N m^{-2} s^{-1} (light lines). (b) N_2O fluxes in response to fertilizer application. Data are averages of five fertilizer chase experiments ± SE. The average response to fertilization lasted for eight days with an average flux of 25.8 ng N m^{-2} s^{-1} on each day, with low and high-end estimates (means ± SE) of 13.2 ng m^{-2} s^{-1} and 33.3 ng m^{-2} s^{-1}. (c) Conceptualized diagram of modeled annual flux of N_2O for a lawn that is fertilized 15 times per year. (d) Conceptualized diagram of modeled annual flux of N_2O for a lawn that is fertilized 2 times per year.

application (Figure 2b). There was no relationship between N_2O emissions and lawn type (ornamental vs. athletic fields), soil moisture content or soil or air temperature.

[12] In order to estimate total annual N_2O emissions, we estimated the background flux of N_2O as well as pulses observed after fertilizer applications. To estimate background fluxes, we combined measurements from both types of turf taken more than two weeks after fertilizer applications (Figure 2a). Fluxes ranged from −0.5 to 33.0 ng N m^{-2} s^{-1}, within the range of values reported for agricultural grasslands (0–10 ng N m^{-2} s^{-1}) [*Flechard et al.*, 2007]. The median N_2O flux was 2.0 ng N m^{-2} s^{-1} (Figure 2a).

[13] To estimate the contribution of fertilizer-related N_2O emissions to the total annual flux, we measured fluxes immediately after fertilization events. Although the exact fertilizer amount applied by landscaping contractors is unknown, we were able to coordinate N_2O flux sampling with five fertilizer applications. The average increase in N_2O emissions lasted eight days and resulted in an average flux of 25.8 ng N m^{-2} s^{-1} (Figure 2b). However, the response to fertilization was highly variable, with maximum observed fluxes of up to 200 ng N m^{-2} s^{-1}.

[14] To estimate annual N_2O fluxes, we combined our results for N_2O pulse following fertilization with the median background flux. The City of Irvine recommends fertilizing 2 to 15 times per year at ∼5 g N m^{-2} with a variety of synthetic, inorganic fertilizers. Therefore, to estimate total annual N_2O emissions, we applied our average fertilizer pulse 15 times during the year (at 8 days for each pulse) for a high-end estimate (Figure 2c), and twice during the year for a lower-end estimate (Figure 2d). The remaining days were assumed to have the baseline flux of 2.0 ng N m^{-2} s^{-1}. The fertilization rate for the low-end estimate is approximately 10 g N m^{-2} yr^{-1} (2 yr^{-1} × 5 g N m^{-2}) and the high-end estimate is 75 g N m^{-2} yr^{-1} (15 yr^{-1} × 5 g N m^{-2}).

[15] Based on these estimates, the annual N_2O emissions range from 0.1 to 0.3 g N m^{-2} yr^{-1}, depending on fertilization rate (Figure 3a). This is substantially less than the annual N_2O flux from an intensively grazed grassland in Ireland (1.8 g m^{-2} yr^{-1}) [*Scanlon and Kiely*, 2003], but higher than estimates for ungrazed, fertilized grasslands in Europe (median = 0.06 g m^{-2} yr^{-1}, range ∼ 0.01 – 0.4 g N m^{-2} yr^{-1}) [*Flechard et al.*, 2007]. Our annual estimates also fall within the range reported for annual N_2O fluxes from urban turf in other studies (0.05– 0.6 g N m^{-2} yr^{-1}) [*Guilbault and Matthias*, 1998; *Kaye et al.*, 2004; *Groffman et al.*, 2009]. Our estimates are lower than expected: we hypothesized that N_2O fluxes from our Mediterranean-climate sites with year-round fertilization would be higher

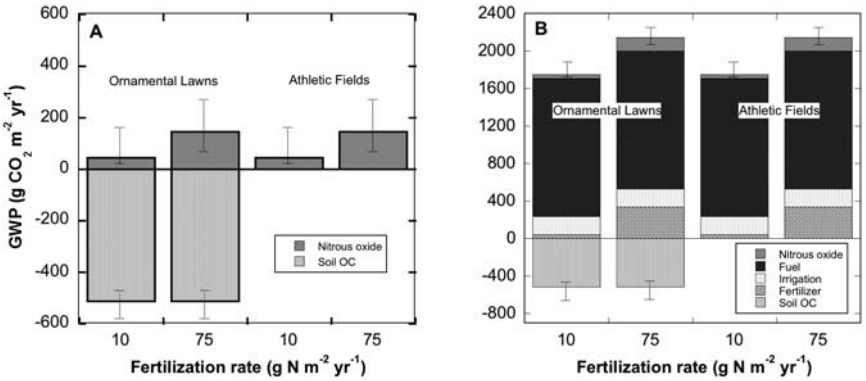

Figure 3. (a) Global warming potential of soil OC sequestration and N_2O emissions in ornamental lawns and athletic fields. Error in GWP-N_2O is based on the mean fertilizer pulse ± its SE, ± the 25% or 75% interquartile of the baseline flux. Error in soil GWP is estimated from the mean OC stock at each time point ± SE. (b) Same as Figure 3a, but including estimates of CO_2 emissions from fuel use, fertilizer production, and irrigation.

than from temperate turf. This may indicate high N uptake by roots due to frequent mowing [e.g., *Kammann et al.*, 1998] or large dissolved losses of N by leaching [*Groffman et al.*, 2009]. Future studies of urban ecosystems would benefit from a full accounting of N stocks and fluxes.

[16] We calculated the contribution of OC uptake and N_2O emissions to the total GWP (in g CO_2 m^{-2} yr^{-1}) of each type of turf (Figure 3a). N_2O emissions of 0.10–0.31 g N m^{-2} yr^{-1} (depending on fertilization rate) correspond to a GWP of +45 to +145 g CO_2 m^{-2} yr^{-1} (Figure 3a). In ornamental lawns, OC storage rates of 140 g C m^{-2} yr^{-1} correspond to a GWP of −513 g CO_2 m^{-2} yr^{-1} greater than the GWP of N_2O emissions. In athletic fields, there is no net storage of CO_2 to offset N_2O emissions. Overall, according to our careful measurements, N_2O emissions are too low to overcome the high rates of OC sequestration in ornamental lawns (Figure 3a).

[17] High CO_2 uptake in lawns is not without a "carbon cost" from fossil fuel CO_2 emitted during maintenance. We made rough estimates of CO_2 emissions derived from fuel consumption, irrigation and fertilizer production. Park management contractors use a reported 2700 gallons of gasoline per month for transportation, mowing, and leaf blowing in Irvine (about 2×10^6 m^2 total park area). We assumed that one gallon of gasoline equaled 2421 g C [*Environmental Protection Agency*, 2005] and that combustion efficiency was 85%, similar to farm equipment [*Lal*, 2004]. This results in annual CO_2 emissions from fuel of 1469 g CO_2 m^{-2} yr^{-1}, about 3 times more than OC storage per m^{-2} in ornamental lawn soils (Figure 3b). Pumping of irrigation water consumes energy at about 53 g C m^{-2} yr^{-1} [*Schlesinger*, 1999], or 193 g CO_2 m^{-2} yr^{-1} (Figure 3b). CO_2 is also formed during fertilizer production via the Haber-Bosch process and during transport and application, producing about 1.436 moles of C per mole of N produced [*Schlesinger*, 1999]. In the current study, this corresponds to emissions of 45 to 339 g CO_2 m^{-2} yr^{-1} for low and high fertilizer regimes (Figure 3b).

[18] Our work clearly shows that high OC sequestration rates in some turfs are dwarfed by soil N_2O emissions and CO_2 released during management, with a total GWP of ornamental lawns of +1238 to +1632 g CO_2 m^{-2} yr^{-1}, depending on fertilization rate (Figure 3b). Because athletic fields do not store OC, they have a total GWP of +1752 to +2145 g CO_2 m^{-2} yr^{-1} (Figure 3b).

[19] A further analysis might consider the impact of lawns on methane (CH_4; GWP ∼ 20x CO_2) balance in cities, as urban lawns have a reduced capacity (13–50%) to absorb atmospheric CH_4 compared to native soils [*Kaye et al.*, 2004; *Groffman and Pouyat*, 2009]. N_2O emissions from lawns are within the range for agricultural soils, so regional N_2O budgets should not ignore urban soils. Future analyses of biological carbon sinks must include a full accounting of GHG emissions including N_2O. Simple accounting of carbon stocks does not accurately represent the effect of terrestrial ecosystems on climate.

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References

Barford, C. C., S. C. Wofsy, M. L. Goulden, J. W. Munger, E. H. Pyle, S. P. Urbanski, L. Hutyra, S. R. Saleska, D. Fitzjarrald, and K. Moore (2001), Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest, *Science*, *294*, 1688–1691, doi:10.1126/science.1062962.

Bijoor, N. S., C. I. Czimczik, D. E. Pataki, and S. A. Billings (2008), Effects of temperature and fertilization on nitrogen cycling and community composition of an urban lawn, *Global Change Biol.*, *14*, 2119–2131, doi:10.1111/j.1365-2486.2008.01617.x.

Churkina, G., D. Brown, and G. Keoleian (2009), Carbon stored in human settlements: The conterminous United States, *Global Change Biol.*, *16*, 135–143, doi:10.1111/j.1365-2486.2009.02002.x.

Environmental Protection Agency (2005), Emission facts: Average carbon dioxide emissions resulting from gasoline and diesel fuel, *Rep. EPA420-F-05-001*, Environ. Prot. Agency, Washington, D. C.

Flechard, C. R., et al. (2007), Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe, *Agric. Ecosyst. Environ.*, *121*, 135–152, doi:10.1016/j.agee.2006.12.024.

Forster, P., et al. (2007), Changes in atmospheric constituents and radiative forcing, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 129–234, Cambridge Univ. Press, New York.

Groffman, P. M., and R. V. Pouyat (2009), Methane uptake in urban forests and lawns, *Environ. Sci. Technol.*, *43*, 5229–5235, doi:10.1021/es803720h.

Groffman, P. M., C. O. Williams, R. V. Pouyat, L. E. Band, and I. D. Yesilonis (2009), Nitrate leaching and nitrous oxide flux in urban forests and grasslands, *J. Environ. Qual.*, *38*, 1848–1860, doi:10.2134/jeq2008.0521.

Guilbault, M. R., and A. D. Matthias (1998), Emissions of N_2O from Sonoran Desert and effluent-irrigated grass ecosystems, *J. Arid Environ.*, *38*, 87–98, doi:10.1006/jare.1997.0300.

Hall, S. J., D. Huber, and N. B. Grimm (2008), Soil N_2O and NO emissions from an arid, urban ecosystem, *J. Geophys. Res.*, *113*, G01016, doi:10.1029/2007JG000523.

Kammann, C., L. Grünhage, C. Müller, S. Jacobi, and H. J. Jäger (1998), Seasonal variability and mitigation options for N_2O emissions from differently managed grasslands, *Environ. Pollut.*, *102*, 179-186, doi:10.1016/S0269-7491(98)80031-6.

Kaye, J. P., I. C. Burke, A. R. Mosier, and J. P. Guerschman (2004), Methane and nitrous oxide fluxes from urban soils to the atmosphere, *Ecol. Appl.*, *14*, 975–981, doi:10.1890/03-5115.

Lal, R. (2004), Carbon emission from farm operations, *Environ. Int.*, *30*, 981–990, doi:10.1016/j.envint.2004.03.005.

Matson, P. A., W. J. Parton, A. G. Power, and M. J. Swift (1997), Agricultural intensification and ecosystem properties, *Science*, *277*, 504–509, doi:10.1126/science.277.5325.504.

McLauchlan, K. (2006), The nature and longevity of agricultural impacts on soil carbon and nutrients: A review, *Ecosystems*, *9*, 1364–1382, doi:10.1007/s10021-005-0135-1.

Milesi, C., S. W. Running, C. D. Elvidge, B. T. Tuttle, and R. R. Nemani (2005), Mapping and modeling the biogeochemical cycling of turf grasses in the United States, *Environ. Manage.*, *36*, 426–438, doi:10.1007/s00267-004-0316-2.

Pataki, D. E., et al. (2006), Urban ecosystems and the North American carbon cycle, *Global Change Biol.*, *12*, 2092–2102, doi:10.1111/j.1365-2486.2006.01242.x.

Pouyat, R. V., I. D. Yesilonis, and N. E. Golubiewski (2009), A comparison of soil organic carbon stocks between residential turf grass and native soil, *Urban Ecosyst.*, *12*, 45–62, doi:10.1007/s11252-008-0059-6.

Robbins, P., and T. Birkenholtz (2003), Turfgrass revolution: Measuring the expansion of the American lawn, *Land Use Policy*, *20*, 181–194, doi:10.1016/S0264-8377(03)00006-1.

Robertson, G. P., E. A. Paul, and R. R. Harwood (2000), Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere, *Science*, *289*, 1922–1925, doi:10.1126/science.289.5486.1922.

Scanlon, T. M., and G. Kiely (2003), Ecosystem-scale measurements of nitrous oxide fluxes for an intensely grazed, fertilized grassland, *Geophys. Res. Lett.*, *30*(16), 1852, doi:10.1029/2003GL017454.

Schlesinger, W. H. (1999), Carbon sequestration in soils, *Science*, *284*, 2095, doi:10.1126/science.284.5423.2095.

U.S. Department of Agriculture (1978), Soil survey of Orange County and western part of Riverside County, 147 pp., Soil Conserv. Serv., Washington, D. C.

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