Carbon stocks and fluxes from residential lands: Turfgrass biomass and productivity

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ABSTRACT

Residential lawns are important contributors to regional ecosystem dynamics in human-dominated landscapes but little is known about how residential lands cycle carbon (C). We are presenting results on urban grassland biomass and productivity from a larger NSF-funded study designed to test the relative strengths of multiple drivers of C stocks and fluxes in residential landscapes. Thirty-three residential sites were selected from within the Gwynns Fall watershed of Baltimore, Maryland. These parcels characterize residential conditions in the region and provide contrasts in urban ecosystem structure (density of coarse vegetation and built structures), historical land use, and current land management practices. Aboveground net primary productivity (ANPP) was measured from bi-weekly collection of lawn clippings and sequential (bimonthly) cores for stubble, thatch, and moss collected from spring 2006 to fall 2007. Interannual variability between the two seasons indicated management inputs such as water availability at the parcel level might be a stronger driver of lawn ANPP than characteristics of the urbanized landscape or biophysical relationships. Care should be used when calculating ANPP, we found significant differences in lawn ANPP when comparing estimates calculated using turnover rates specific to our study sites versus previously published values. Thatch production on our lawns comprised 14-59% of ANPP and moss was present on 90% of lawns, as little information is available regarding how to characterize these components and clarify their

role in lawn productivity further method development is warranted. This work provides context for understanding the impact of urban expansion on regional ecosystem carbon dynamics and identifies the need for standardized methods for measuring lawn ANPP in urban systems.

Keywords: Carbon, urban grasslands, turfgrass, aboveground net primary productivity

INTRODUCTION

Lawns are an important component of the urban and suburban landscape. Grass and soil cover 20.8% of the land area in Brooklyn, NY (Nowak et al. 2002), and an analysis in Franklin County, OH indicated that the county-wide proportion of each residential lot in lawn is 0.816, such that ~23% of the total land surface in the county is covered with turfgrass (Robbins and Birkenholtz 2003). Turfgrass contributes significantly to the landscape even in arid environments: an analysis of satellite imagery in Albuquerque, NM found that turfgrass covered 30.0% of the metropolitan area, and that of this area, 85.0% occurred in home lawns, 8.3% in parks, and 6.7% in golf courses (Blanco-Montero et al. 1995).

Most assessments of turf production have focused on scoring aesthetic quality rather than quantifying yield and production, and the vast majority of published production measurements have been developed using University test plots rather than *in situ* residential systems. The few data available, however, suggest that production can be quite high. For example, Falk (1980) estimated roughly 1650 g m^{-2} yr^{-1} for lawns in Maryland, and Falk (1976) estimated 1020 g m^{-2} yr^{-1} for a lawn in California. If we assume that, on average, the proportion carbon (C) in grass is 0.4268 (Jo and McPherson 1995), then these data suggest that annual grass production in lawns could range from 4 to 7 Mg C ha^{-1} yr^{-1}, while live trees in the average US forest typically add only 1.12 Mg C ha^{-1} yr^{-1} (Birdsey 1992). Differences among grass species may impact productivity, but published data suggest little difference among grass species in daily clipping yield (Hull 1992). We note that mowing tends to create a thick mat of vegetation between 5 cm above and 5 cm below the soil surface, such that clipping removes only between 3% and 20% of annual production (Madison 1971, Falk 1980, Qian et al. 2003). As a result, estimates of productivity based on clipping alone are likely to underestimate annual lawn production.

Variations in management practices are likely to impact aboveground grass production. The inherent N levels in soil are rarely optimal for turfgrass, so N additions typically increase production (Heckman et al. 2000, Gaudreau et al. 2002, Kopp and Guillard 2002) and recent surveys in Maryland and North Carolina found that a majority of homeowners apply fertilizer to their lawns (Law et al. 2004, Osmond and Hardy 2004). Typical water use by turfgrass varies from 2.5 to 7.5 mm day$_{-1}$, with maximum values as high as 12 mm day$_{-1}$ (Kneebone et al. 1992). In Baltimore's temperate climate, irrigation may be necessary for aesthetic purposes, especially in dry years, but is probably not critical to grass survival: still, unless rainfall equals photosynthetic and evaporative demand, lawns irrigated to avoid water stress are likely to be growing more quickly.

To quantify carbon pools and processes in urban ecosystems, researchers use metrics that are well studied in natural forest and grassland systems such as net primary productivity (NPP). NPP is a metric for the accumulation of C or biomass per unit area per unit time (Roy and Saugier 2001; Lauenroth, Scurlock) and is an important ecosystem characteristic for understanding the flux and storage of C in a system. NPP is reported on an annual basis and accounts for change that occurred in aboveground biomass plus losses such as decomposition. Previous studies that have measured NPP on urban grasslands (Qian, Golubiewski, Kaye, Jo and McPherson) have followed the methodology and published productivity turnover values derived by Falk (1976, 1980) which are each based on a small sample size (1 and 2 lawns respectively). Further research is needed to quantify the aboveground lawn productivity pools over a larger set of data to explore the viability of these methods to correctly capture the productivity of urban grasslands.

Need to add a paragraph on bigger picture importance*: Tie in how with urban expansion we are increasing the amount of urbanized land in turn increasing the amount of lawn. And what impacts will this change C cycling in these environments…*

The goal of this research is to gain a better understanding of the processes driving C sequestration and storage in urban residential systems and test methods that can be used in assessments of C cycling in residential areas in other regions. Our primary research objective was to quantify key carbon stocks and fluxes in the residential urban grasslands within the Gwynns Falls watershed in Baltimore, Maryland. Our second objective was to identify the relative importance of natural and anthropogenic (management, urban landscape structure, land use history) variables as drivers of production in these urban grassland systems.

METHODS

Site description

This research is part of the Baltimore Ecosystem Study (BES), one of two NSF-funded urban Long-Term Ecological Research (LTER) sites in the United States, established in 1997. The study area was focused on three residential neighborhoods (Rognel Heights, Glyndon, and Baismans Run) within the Gwynns Falls watershed in Baltimore, Maryland (Figure 1) that fall along an urban-to-rural gradient and have been found to represent the range of residential conditions in the region (Groffman et al. 2004, Law et al. 2004). Rognel Heights falls primarily within Baltimore City, while Glyndon and Baismans Run fall just outside the Baltimore City limits, in the adjacent Baltimore County. The soil type in the study region can be classified as Manor and Legore soil series; both are very deep, well-drained soils on uplands, with loamy textures and bedrock at 5 to 10 feet below the soil surface (NRCS 1976, 1998). In the Baltimore, Maryland region the mean annual precipitation from 2005 to 2007 was 1078 mm and the mean annual temperature of 13.8°C (weatherunderground…replace with NOAA data). *[Need to expand climate information: provide Balt City vs County precip #s as will make a difference]*

Sampling Design

Study sites were delineated by property boundaries and restricted to single-family housing or non-connected single-family homes as explicit permission had to be obtained from landowners to install sampling equipment and to access their property. Sites were randomly selected based on four stratifying elements: housing age, prior land use (i.e. the land use immediately prior to residential development), level of coarse vegetation density and level of built structure density. The housing age or the year the house was built was acquired from the Maryland PropertyView database and was used to capture temporal changes that can occur in the soil environment post development (Qian and Follett 2003). Houses built before 1900 were not included in this analysis because of the potential for error in the PropertyView database measuring housing age. Housing age was classified into four categories for site stratification: 0-10, 10-30, 30-50, and greater than 50 years old. Prior land use was determined based on land use change detection classifications developed for 1938, 1957, 1971, and 1999 (Wehling X). Wehling (X) defined categories to distinguish between homes that were designated as forest or agriculture immediately prior to the residential land use. Homes that were 10-30 years old, for example, were classified as formerly agricultural if their value in 1971 was an agricultural category. Sites that had transitional periods between categories were not considered, for example if the 1957 value was agricultural, the 1971 value was "transitional", and the 1999 value was urban, the homes were not considered as candidates. An urban land classification, HERCULES 6.0 (Cadenasso et al.), defines urban ecosystem structure along gradients of housing and tree density and was used to distinguish coarse vegetation density and built structure density at the parcel level. Coarse vegetation density categorizes the percent tree or shrub cover on a parcel and values range from 2-present (up to 10%) tree or shrub cover, 3-low (11-35%), 4-medium (36-75%), and 5-high (>75%). Similarly, structure density categorizes the percent of the parcel footprint covered by built features and ranges from 1-low (up to 35%), 2-medium (36-75%), and 3-high (>75%). For each combination of site stratification variables, only categories that contained ten or more candidate sites were included in the study design (Table 1).

Candidate households within the study design categories were sent a mailing with information regarding the study and a study involvement form with a pre-addressed envelope that willing participants could return. We aimed to acquire four residential lawn replicates per category for study involvement. Twenty-two study sites were established in 2006 with twelve additional plots added for 2007 for a total of 33 sites. A total of 21 plots have two seasons of data; one homeowner discontinued the study during the 2007 season.

Measuring vegetative components

On the turfgrass portion of each parcel a 0.5 x 0.5 m square microplot was established for sampling grass production. The location of the plot was consulted with landowners to identify potential areas to avoid before using random numbers for final plot placement. To estimate aboveground annual production we quantified turf clippings, stubble, thatch, and moss over a growing season as defined by April 1-November 15th. *[First yr some sites were not setup until early May]*. Clipping yield was determined by mowing the grass microplots once weekly or biweekly during the growing season and collecting the clippings using a portable vacuum cleaner (Falk 1980). Clippings were oven dried for 48 hours at 75°C and weighed. A subsample of the clippings *per site per year* was ground in a Wiley mill to pass a 40 mesh screen and analyzed for C and N content (Carlo-Erba CN analyzer). Thatch, stubble, and moss biomass were found by coring at 2-month intervals year-round (April, June, August, October). Three cores (roughly 5-cm by 10-cm deep) were collected per sampling interval from the grass portion of the parcel, outside the microplot and the live and dead organic matter were sorted, dried, and weighed.

Stubble was classified as the live vegetation growing horizontally in the core and thatch defined a loose intermingled layer of dead and living shoots, stems and rhizomes the develops between the stubble and soil surface (Schlossberg et al. 2008). The percent moss cover was recorded for each core.

Total turfgrass production was calculated annually as the sum of live + dead production as described by Falk (1976, 1980) and Qian et al. (2003). Specifically, turfgrass aboveground net primary productivity (ANPP) was calculated as: ANPP = total clipping biomass + (stubble maximum * stubble turnover rate) + (thatch maximum * thatch turnover rate) + (moss maximum * moss turnover rate). Annual clipping biomass was defined as the sum of the dry clipping mass collected over the season. Annual stubble, thatch and moss production were calculated by multiplying the maximum standing crop biomass value from sampled cores for that season by the individual turnover rate. Individual lawn turnover rates of stubble and thatch were calculated from the ratio of annual production to total mass (Dahlman and Kucera 1965, Falk 1976, Falk 1980, Qian et al. 2003). This method assumes that any live biomass carried over from the previous year is excluded. As no published methods were identified for moss production in grasslands, moss productivity and turnover were calculated similarly to stubble and thatch when moss was present on more than one of the four annual cores. In instances where moss only occurred during one of the four sampling periods a turnover rate was not applied.

The dry weight of the clippings and stubble were converted to grams of carbon by multiplying by 0.4585, the measured average percent carbon of clippings in this study. Thatch was converted to grams of carbon using a value of 0.5735 based on the average percent carbon of the clippings and adjusted for the higher lignin content in the thatch compared to the shoots (Qian et al. 2003; ICF report/EPA source). A carbon concentration value of 0.43 was used for moss as identified by Vingani et al. (2004) as the percent carbon content of *Sphagnum capillifolium*.

Measuring soil components

Soil respiration was measured from permanent chamber bases (10 cm diameter, 2 per plot) from within the turfgrass microplot. Soil respiration rates were measured in situ using a Li-Cor 8100 portable soil CO_2 flux measurement. Measurements were taken weekly and were the first thing measured at each site to minimize soil disturbance around the soil collars. Soil temperature (at soil surface, 5 cm, and 10 cm depths) and moisture (Trase System) were measured directly following soil respiration measurements and used to develop annual estimates of flux. Grass was present within the respiration chamber collars therefore we used a correction factor of X to account for dark respiration of the turf vegetation present (CITE). The corrected respiration value is a measure of soil and root respiration; in natural grasslands root respiration can contribute 17-40% of the total soil CO2 flux (Raich and Tufekcioglue 2001).

Soil cores were collected during a single sampling period (DATE?) from two sites on the lawn and sampled to a depth of 100 cm at each plot using an intact-core soil sampling device that allowed for calculation of bulk density. Soils were analyzed for total C and N using a Carlo-Erba CN analyzer and soil particle size analysis. This data is described further by Raciti (unpublished data). As the majority of root systems for turfgrass are concentrated in the surface soil layers, we will be using soil measurements to a depth of 30cm for this analysis (Barton et al. 2006).

Lawn management survey

A survey of the lawn care practices (after Law et al. 2004) was administered to homeowners participating in the study to quantify the relationships between land management practices and the measured C stocks and fluxes. The survey identified whether the lawn received fertilizer applications within the past 12 months and if the homeowner irrigated the lawn.

Statistics

Since equal replicates were not attained for each category, there are not enough observations to perform pair-wise cluster comparisons as originally designed. The relationships between the site selection categories were explored for covariation as the Gwynns Falls watershed did not contain all possible combinations of site stratification variables for a full factorial design. As was previously mentioned, only categories that contained ten or more candidate sites were included in the study design. A Mann Whitney test confirmed that prior land use and coarse vegetation density as well as prior land use and structure density are highly related using a p-value of 0.05. The formerly forested sites were associated with higher levels of coarse vegetation and structure density compared to formerly agricultural sites in this region. Based on these results coarse vegetation density and built structure density were dropped from further statistical analysis. Prior land use will be considered a proxy for coarse vegetation density and built structure density. The age of the development was used as a continuous variable in the analysis based on the actual year the house was built.

Urban grassland productivity, ANPP and clipping biomass, were analyzed with an analysis of variance (ANOVA) to test for significant housing age and prior land use main effects. Paired t-tests were used to explore the interannual variability of the aboveground productivity measures. An unpaired two-sample t-test was used to test for differences in lawn management practices on productivity and respiration measures. All statistical analyses were performed using SAS 9.1 software package and significance was verified using a p-value of 0.10.

RESULTS

Urban grassland ANPP

Lawn ANPP and biomass production components among all sites were highly variable for both growing seasons (Table 2). Total ANPP for the 2006 (n=22) and 2007 (n=32) growing seasons ranged from 82 to 1311 g biomass m^{-2} yr^{-1} (n=54). Production from each of the individual lawn components for both seasons (n=54) had a broad range (clippings 0-788 g m^{-2} yr^{-1}, stubble 23-328 g m^{-2} yr^{-1}, thatch 29-517 g m^{-2} yr^{-1}, moss 0-563 g m^{-2} yr^{-1}). The average turnover rate for stubble was 0.58 or approximately 1.8 years and thatch ranged from 0.73-0.86 or 1.16-1.4 years (Table 3). The moss turnover rate, calculated when moss frequency was greater than 1, ranged from 0.64-0.67.

Interannual effects on productivity were compared on a subset of the sites that had two full seasons of productivity measurements (n=21). Total aboveground productivity was not significantly different between the two seasons, however there were significant interannual differences between clipping biomass and thatch production (Table 4). Clipping biomass was higher in 2006 (p=0.001) than in 2007 and thatch has the opposite relationship of higher thatch production in 2007 (p=0.09). The stubble and moss components did not differ significantly between the two seasons. This trend is repeated when looking at the percent contribution of each component to ANPP (Figure 2). Clipping biomass contributes to 20-54% of the total ANPP in 2006 and 9-38% in 2007 while thatch contributes 14-40% in 2006 and 24-59% in 2007. Stubble contributed to roughly a third of the aboveground production in 2006 (28 +/- 12%, mean +/- 1 SD) and 2007 (24 +/- 11%). On average, moss contributed to less than a quarter of the total ANPP in 2006 (8 +/- 8%) and 2007 (12 +/- 17%).

Anthropogenic drivers of productivity

External inputs to the lawn were assessed from surveys of homeowner lawn management practices that were completed from 27 of the 32 households. On these 27 sites, 20 lawns were fertilized within the past 12 months, 11 of the 20 homeowners that reported fertilizing their lawn used a professional lawn care service. Twenty homeowners reported watering their lawn and grass clippings were often left on the lawn (n=22) as opposed to being bagging and removing from the site (n=5). Based on the results from this survey, fertilizer and water use did not significantly influence measures of lawn productivity in 2006 or 2007. Fertilized lawns (n=20) did have higher nitrogen content in lawn clippings in 2007 (p=0.07) compared to unfertilized lawns (n=7). Mowing height, the height of the stubble after being mown, was recorded in the field and was not found to correlate to total clipping biomass.

Prior land use was found to influence ANPP and clipping biomass. Aboveground NPP was found to be significantly higher on lawns that were previous agricultural land in 2006 (p=0.008, n=22) and 2007 (p=0.03, n=32). Similarly, clipping biomass was significantly higher on previously agricultural sites in 2007 (p=0.003, n=32). The age of the development did not have an influence on either productivity measure.

Biophysical drivers of productivity

Relationships between lawn primary productivity and measured soil and plant tissue variables were explored to identify if natural biophysical relationships influenced productivity in urban grassland systems. Annual respiration (soil + root respiration) had a positive correlation to both annual clipping biomass (Figure 4) and ANPP. Lawn aboveground productivity did not correlate to lawn N and C foliar tissue content or the soil C and N content (at depths 0-10cm and 10-30cm).

DISCUSSION

Comparisons of urban grassland productivity

A small number of studies exist that are aimed at quantifying and measuring productivity in urban grasslands (Kaye et al. 2005; Jo and McPherson 1995; Golubiewski 2006; Falk 1978, Falk 1980). The measured ANPP from both seasons of this study fall well within the range of published values of urban grassland productivity (Table 5). The range in ANPP from our study (82-1311 g m^{-2} yr^{-1}) closely correspond to that of Golubiewski (2006) (80-1228 g m^{-2} yr^{-1}) and depicts the variation that can occur over larger sample sizes. We identified that clippings, stubble, and thatch are equally important contributors to ANPP (Figure 2, Table 4). The mean clipping yields from our Maryland lawns are similar to Golubiewski's (2006) yields from lawns in Colorado of 298 g m^{-2} yr^{-1}. Qian et al. (2003) measured lawn production (n=12) on a turfgrass research facility and reported higher mean clipping yield (470 g m^{-2} yr^{-1}) and thatch production (436 g m^{-2} yr^{-1}) but had similar stubble production of 179 g m^{-2} yr^{-1} to our lawns. The higher productivity measured by Qian et al. (2003) may be attributable to the plots having a more controlled environment with multiple fertilizer applications and regular irrigation.

It is important to note that the methodology used to quantify urban grassland productivity varies between these studies in their inclusion and measurement of productivity components, and whether measured or published values were used in the calculations. Falk (1978) estimated total net primary productivity (above- and belowground) using the following equation:

$$TNPP = \text{Sum clipping biomass} + (S_{max} * S_{turnover}) + (R_{max} * R_{turnover})$$

where S_{max} = stubble maximum standing crop, $S_{turnover}$ = stubble turnover rate, R_{max} = root maximum standing crop, $R_{turnover}$ = root turnover rate. The aboveground components (clipping and stubble) in Falk's equation have been the basis for measuring productivity in published urban grassland literature (Falk, Qian, Golubiewski, Kaye, Jo and McPherson). All studies measured clipping biomass by harvesting clippings during the growing season but stubble measurements between these studies vary in sampling frequency where they may have only been sampled two times during the year (Qian et al 2003) or only measured at the end of growing season (Golubiewski 2006, Kaye et al. 2005). This can lead to underestimations in the component productivity if the true peak was not captured during sampling.

Our study calculated individual turnover rates per lawn based on the values from the seasonal cores collected and those rates were incorporated into our ANPP estimate. Many studies use the published turnover rates for stubble and roots from Falk (1976, 1980) and Jo and McPherson (1995). A comparison between our ANPP estimates using the individual lawn derived turnover rate to an estimate based on published values for stubble (0.56) and thatch (0.54) identified a significant difference (p-value 0.01) between the paired ANPP calculations (Falk 1976, Falk 1980, Qian et al. 2003). This difference is likely explained by the wide range in individual lawn turnover rates as stubble and thatch rates ranged from 0.2-0.85 and 0.46-0.96 respectively and the published value used for thatch is considerably lower than the average thatch turnover of 0.73 and 0.86 in this study (Table 3). Due to the discrepancies in productivity from turnover rate used, future studies should consider the measurement of site specific turnover rates to help clarify the variation in this measurement.

Further consideration is also needed on which components constitute the aboveground productivity of the urban grasslands. This study included thatch and moss as lawn aboveground components of productivity. The inclusion of thatch in the aboveground component may lead to an overestimation of aboveground productivity as it is an intermingled layer of living and dead organic matter situated between the stubble and root-soil interface (Schlossberg 2008). However thatch biomass can be a considerable component of the lawn and there are currently no published methods as to how to parse out the aboveground versus belowground differences in thatch. Qian et al. (2002) measured thatch productivity as part of the TNPP and considered thatch a belowground component. In the turf management literature thatch is measured in terms of depth or thickness and dry mass (cite) but these measurements are used in the context of evaluating management practices that reduce thatch accumulation. Thatch is seen as an undesirable element of the lawn as it is attributed with a low water holding capacity, reducing turf tolerance to extreme temps, and reducing pesticide effectiveness (McCarty et al. 2005; Raturi et al. 2004, Schlossberg 2008).

Moss is a component that has not been previously discussed in urban grassland productivity and similar to thatch, turfgrass management literature address moss under the umbrella of methods for eradicating moss presence for a healthy lawn (Cite). The lack of moss inclusion in other studies may be attributed to climate differences, as the majority of the studies were conducted in drier western regions (Qian, Falk, Kaye, Golubiewski). In our study moss occurred on at least one of the four cores sampled on 30 of the 33 sites and it could comprise up to 100% cover of the core measured. As the presence of moss and grass may not always co-occur, meaning if 30% of the core was moss, stubble and thatch may only comprise 70% of the cover, than moss can be a considerable contributor to the urban lawn productivity. Moss productivity methods currently identified for tundra, forest and peatland communities, are based on measuring moss growth in terms of shoot length and converted to mass for moss production (Vitt 2007). As moss was not a predetermined variable of measurement in this study we were only able to estimate moss based on mass alone. As with thatch, moss is a component that may be comprised of aboveground and belowground productivity, so our inclusion of moss in the aboveground measurement may lead an to overestimation (Vitt 2007).

All measurements of total NPP will to some extent be an underestimate since NPP is not a metric that can be directly measured (cite). Nevertheless in order to be able to fully quantify the function urban grassland components have in terms of lawn productivity and C cycling, clarification is needed on methods for estimating the productivity of thatch and moss and a consensus on whether they are contributing to aboveground or belowground C pools.

Seasonal differences in aboveground productivity

The interannual differences of reduced clipping biomass and increased thatch production in 2007 may relate to differences in total precipitation during the growing season (April 1st to November 15th) for those years. For the Baltimore, Maryland region the total growing season precipitation was 796 mm in 2006 and 561 mm in 2007 (Figure 3). The reduced turf productivity in 2007 could be attributed to the lower rainfall received and this drier climate slowed thatch decomposition accounting for the increased thatch accumulation (McCarty et al. 2005; Sala 2001). Annual respiration also displayed an interannual trend with lawns having significantly (n=21, p=0.0023) lower respiration in 2007. This reduced respiration rate could be a combined impact of reduced precipitation and a change to the soil microclimate by the increase in thatch (Raich and Tufekcioglue 2001). This strong trend between seasons is likely driven by a water limitation in these lawns, neighborhood specific precipitation measures would be needed to better under the strength of this relationship as total precipitation has been found to vary across the Gwynns Falls study region.

Biophysical and human-mediated drivers of productivity

Management of urban grasslands

Lawn management, fertilization and irrigation, have been found to have a strong influences on aboveground productivity. Although this study was unable to detect the impacts of homeowner lawn management on aboveground productivity, other studies have found that fertilization and water use increase lawn production. Golubiewski (2006) identified that the amount of fertilizer applied to lawns influenced aboveground productivity where lawns receiving higher amounts of fertilizer had increased biomass and productivity. Research at a turf facitility in Ohio found increased clipping biomass from applications of compost biosolids (Garling and Boehm 2001). The finding of higher N content in the clipping biomass from fertilized lawns in 2007 corresponds to other studies that have identified lawn N content to increase proportionally to the amount of fertilizer applied (Golubiewski 2006; Turner and Hummel 1992; Kopp and Gillard 2002).

Another lawn management practice that could influence the productivity is the lawn mowing height. We were not able to detect a difference in the lawn height and the amount of biomass produced from our two seasons of data. However, a controlled study done on a turf research facility identified that shorter lawns (5cm) produced more aboveground biomass than lawns left at a taller height (10cm) (Lily unpublished data).

There are several variables that could be obscuring the effects of fertilizer on aboveground productivity in our study. The lack of available data to pre-stratify sites based on homeowner management regime resulted in over 70% of the study lawns reported as applying fertilizer in the past 12 months. Of the lawns that were fertilized, we were unable to quantify fertilizer amount based on the survey administered and homeowner response. In addition, the survey was only administered once to residents during the entire study period and may not have been reflective of homeowner behavior for both years of data collected. Garling and Boehm (2001) found turfgrass after nutrient additions had an increased N tissue content however it had a short temporal effect and the N tissue content lowered after 26-50 days.

Anthropogenic drivers of productivity

Aboveground productivity was found to differ depending on the prior land use of the lawn. Both clipping biomass in 2007 and ANPP for both seasons were significantly higher on previously agricultural lawns. One explanation for this relationship could be a legacy effect in the soil physical and chemical properties from prior land use. Qian and Follet (2002) identified golf course fairways less than 10-years old had 24% lower soil organic C if they were previously agricultural land than fairways constructed on native grasslands. However a comparison of soil C and N content at depths 0-10 and 10-30cm in our lawns did not identify significant differences in prior land use. As discussed in the methods section, prior land use is highly related to coarse vegetation density and built structure density therefore these variables could play a role in explaining these differences seen in productivity. As previously agricultural sites were highly related to sites with low tree densities, we could infer that these sites provided less shading and allowed for greater light interception, which would have a positive effect on plant photosynthesis and productivity. Since leaf N content is found to positively correlate to the rate of photosynthesis (Woledge and Pearse 1985) we explored this relationship between leaf N content and plant productivity (clipping biomass) however these two variables were not correlated amongst our lawn sites.

Construction practices involved in developing residential land have a measureable impact on the site soil properties. Several studies have identified a temporal pattern of reduced soil quality after development where younger turf has been found to have lower levels of soil OM (Qian and Follet 2002), reduced microbial biomass (Sharenbroch et al. 2005), and lower soil C and N contents (Golubiewski 2006; Law et al. 2004) that likely correspond to the higher soil bulk density or greater soil compaction of these soils (Bullock and Gregory 1991; Law et al. 2004). Although many of these soil properties and processes could influence aboveground productivity, the age of the development did not correlate to clippings biomass or ANPP. Interestingly we also did not find a temporal relationship between soil C and N content as identified by other studies (Golubiewski 2006; Law et al. 2004; Qian and Follet 2002).

Biophysical drivers of productivity

Many of the biophysical responses in relation to aboveground productivity that can be seen in natural systems were not present at the urban grassland sites. A relationship that was present was the positive correlation between aboveground productivity and annual respiration (soil microbial + root). This association is representative of the plant-soil interaction in which increased aboveground productivity is providing more resources to microbial populations in the form of detritus (dead clippings) and carbon inputs from root exudates. A meta-analysis done by Raich and Tufekcioglue (2001) found this same response in grassland sites. As soil respiration rates are largely determined by soil moisture and temperature (Raich and Tufekcioglue 2001), respiration has been found to correlation to soil texture as a measure of soil porosity, water holding capacity and fertility (Luo & Zhou). We did not identify a relationship with soil texture to soil respiration rates in our study, indicating that respiration rates may be influenced more by climate factors (precipitation) or factors of the managed lawn system. The lack of influence of other soil physical and chemical properties on lawn productivity in our study is similar to findings from Golubiewski (2006) in Colorado lawns and was attributed to the greater influence of the management practices of the lawn.

Foliar N content of plant tissue has been found to be a predictor of plant growth (Loustau et al. 2001) and would be expected if lawns were achieving their maximum photosynthetic rate, but this relationship was not evident among our lawns. Barton et al. (2006) found this relationship to be inconsistent, only 1 out of 4 experimental plots showed this relationship, but did find a stronger tie of foliar N to fertilizer type. This lack of correlation of plant nutrients to production could be due to other variables impeding photosynthesis such as light interception or nitrogen deficiency (Woledge and Pearse 1985).

Limitations on aboveground productivity identified in natural systems may be lifted in urban grasslands where management of the system can be intense. But many standard biogeochemical processes still apply in these urbanized systems.

Constraints on urban grassland research

Conducting research in urban residential ecosystems presents numerous factors that you are unable to control and account for ahead of time such as pet waste and homeowner behavior and activity. In this study there were two variables, lawn management and light availability, that we measured but did not constraint enough to be able to test their effect on lawn productivity. A stronger quantification of current management inputs to the lawn is needed to identify the influence of nutrient additions on productivity of lawns and the temporal scale of management practices. Ideally a survey regarding lawn management could be collected and used for site stratification purposes. The second effect we were unable to distinguish is the influence of light availability on lawn productivity. Although we used coarse vegetation density as a site stratification variable, the tree density on the parcel may not necessarily coincide with the random placement of the established plot.

CONCLUSIONS

NPP is variable and relationships that are found to drive NPP in natural forest and grassland systems do not hold in managed urban systems. We need to better differentiate the biophysical (climate) versus human mediated (management) signals that are impacting these urban residential systems. Information on the C stock and fluxes in residential areas can be utilized in ongoing efforts of characterizing C budgets in urban areas however it is important to find a consensus on how to measure and compartmentalize these urban grassland components in order to apply this work to other regions.

REFERENCES …to be completed (obviously)…

Table 1. Criteria used to stratify sites into clusters; sites were randomly selected from potential pool of identified households or parcels for study participation. (* - less than 20 potential households, exact number unknown).

Cluster	Land Use History	Housing Age	Coarse Vegetation Density	Structure Density	Number of Potential Households	Number of Households Sampled
1	Agricultural	0-10	2	1	15	2
2	Agricultural	10-30	2	1	43	3
3	Forest	0-10	5	2	14	3
4	Forest	10-30	5	2	142	4
5	Forest	30-50	3	2	82	4
6	Agricultural	30-50	3	2	696	4
7	Forest	30-50	3	3	18	4
8	Forest	30-50	4	2	89	4
9	Forest	50+	5	1	*	4
10	Agricultural	50+	5	1	*	1

Table 2. Aboveground biomass production per component and annual aboveground net primary productivity for all sites per year sampled. *[Need to figure out way to make this large table fit! May reduce text with abbreviations…will likely remove first 2 columns and just number 1-32 for sites]*

Cluster	Site Replicate	Year House Developed	Land Use History	Coarse Vegetation Density	Structure Density	Sampling Year	Clipping Biomass (g m2 yr)	Stubble Production (g m2 yr)	Thatch Production (g m2 yr)	Moss Production (g m2 yr)	ANPP (g m2 yr)
1	1	0-10	Ag	2	1	2006	771.8	194.8	343.9	0	1310.5
1	1	0-10	Ag	2	1	2007	302.6	115.9	121.2	0	539.6
1	2	0-10	Ag	2	1	2006	-	-	-	-	-
1	2	0-10	Ag	2	1	2007	436.6	234.1	516.6	0	1187.3
2	1	10-30	Ag	2	1	2006	104.5	46.9	60.3	10.0	221.7
2	1	10-30	Ag	2	1	2007	69.2	104.0	309.5	39.0	521.7
2	2	10-30	Ag	2	1	2006	140.1	116.8	453.4	97.4	807.8
2	2	10-30	Ag	2	1	2007	95.7	111.0	135.9	49.4	392.0
2	3	10-30	Ag	2	1	2006	787.7	90.8	246.0	21.6	1146.0
2	3	10-30	Ag	2	1	2007	392.3	228.4	360.7	5.2	986.6
3	1	0-10	Forest	5	2	2006	190.9	204.2	159.7	2.9	557.6
3	1	0-10	Forest	5	2	2007	107.8	166.0	259.3	49.5	582.6
3	2	0-10	Forest	5	2	2006	236.4	93.6	85.7	0	415.8
3	2	0-10	Forest	5	2	2007	53.0	314.3	117.9	13.5	498.7
3	3	0-10	Forest	5	2	2006	19.4	134.3	124.5	20.5	298.7
3	3	0-10	Forest	5	2	2007	-	-	-	-	-
4	1	10-30	Forest	5	2	2006	62.8	81.7	28.8	60.7	233.9
4	1	10-30	Forest	5	2	2007	44.0	25.3	137.8	563.0	770.1
4	2	10-30	Forest	5	2	2006	-	-	-	-	-
4	2	10-30	Forest	5	2	2007	46.4	142.0	252.3	4.7	445.4
4	3	10-30	Forest	5	2	2006	-	-	-	-	-
4	3	10-30	Forest	5	2	2007	233.2	108.8	321.1	0	663.1
4	4	10-30	Forest	5	2	2006	-	-	-	-	-
4	4	10-30	Forest	5	2	2007	84.1	115.2	190.7	99.5	489.5
5	1	30-50	Forest	3	2	2006	27.2	67.5	102.5	42.6	239.8
5	1	30-50	Forest	3	2	2007	28.8	203.5	280.1	10.4	522.9
5	2	30-50	Forest	3	2	2006	-	-	-	-	-
5	2	30-50	Forest	3	2	2007	161.6	48.7	117.1	0	327.4
5	3	30-50	Forest	3	2	2006	-	-	-	-	-
5	3	30-50	Forest	3	2	2007	32.8	87.6	65.4	40.5	226.3
5	4	30-50	Forest	3	2	2006	341.5	200.4	159.0	0	701.0
5	4	30-50	Forest	3	2	2007	147.0	40.5	261.3	0	448.8
6	1	30-50	Ag	3	2	2006	225.7	126.9	140.6	153.0	646.3
6	1	30-50	Ag	3	2	2007	137.5	77.8	73.7	61.8	350.8
6	2	30-50	Ag	3	2	2006	-	-	-	-	-
6	2	30-50	Ag	3	2	2007	201.7	224.9	199.0	8.8	634.4
6	3	30-50	Ag	3	2	2006	262.5	195.7	77.1	12.7	548.0
6	3	30-50	Ag	3	2	2007	186.9	116.8	73.0	251.3	628.0
6	4	30-50	Ag	3	2	2006	222.4	127.9	173.8	10.7	534.8
6	4	30-50	Ag	3	2	2007	251.2	191.7	303.8	31.2	777.8
7	1	30-50	Forest	3	3	2006	286.1	138.0	44.5	6.8	475.4
7	1	30-50	Forest	3	3	2007	221.2	148.4	115.5	162.3	647.3
7	2	30-50	Forest	3	3	2006	31.6	75.3	28.7	25.3	160.8
7	2	30-50	Forest	3	3	2007	0	92.0	117.9	14.0	223.9
7	3	30-50	Forest	3	3	2006	230.9	127.2	39.5	10.1	407.7
7	3	30-50	Forest	3	3	2007	149.4	65.3	195.6	0.8	411.0
7	4	30-50	Forest	3	3	2006	522.0	165.3	93.1	37.5	818.0
7	4	30-50	Forest	3	3	2007	337.5	208.9	152.0	84.8	783.2
8	1	30-50	Forest	4	2	2006	178.8	282.0	72.2	186.3	719.4
8	1	30-50	Forest	4	2	2007	141.3	84.2	203.1	31.4	460.0
8	2	30-50	Forest	4	2	2006	40.0	168.1	50.4	17.4	275.9
8	2	30-50	Forest	4	2	2007	16.3	104.5	351.1	0	471.9
8	3	30-50	Forest	4	2	2006	130.9	144.7	151.1	5.6	432.2
8	3	30-50	Forest	4	2	2007	57.1	106.7	80.0	79.3	323.1
8	4	30-50	Forest	4	2	2006	89.0	126.6	61.8	38.1	315.4
8	4	30-50	Forest	4	2	2007	50.9	105.8	94.8	93.4	345.0
9	1	>50	Forest	5	1	2006	-	-	-	-	-
9	1	>50	Forest	5	1	2007	13.5	23.0	45.5	0	82.0
9	2	>50	Forest	5	1	2006	-	-	-	-	-
9	2	>50	Forest	5	1	2007	85.5	132.0	273.6	0	491.1
9	3	>50	Forest	5	1	2006	-	-	-	-	-
9	3	>50	Forest	5	1	2007	25.6	184.5	249.2	218.1	677.4
9	4	>50	Forest	5	1	2006	-	-	-	-	-
9	4	>50	Forest	5	1	2007	243.8	310.6	145.8	0	700.1
10	1	>50	Ag	5	1	2006	319.8	327.7	265.2	194.2	1106.9
10	1	>50	Ag	5	1	2007	240.6	190.7	243.5	0	674.8

Table 3. Turnover rates for stubble, thatch, moss components and from this study (2006 and 2007 seasons) and published values. [Moss turnover only for frequency of occurrence >1]

Component	2006	2007	Falk 1976	Falk 1980	Jo & McPherson 1995
Stubble	0.58	0.58	0.49	0.6-0.65	0.5
Thatch	0.73	0.86	-	-	-
Moss	0.67	0.64	-	-	-

Table 4. Aboveground productivity for sites with two seasons of data (n=21, reporting mean (standard error)). [Clippings – total clipping biomass; stubble – stubble production, thatch – thatch production, moss – moss production, ANPP – aboveground net primary productivity].

Source	Clippings ($g\ m^{-2}\ yr^{-1}$)	Stubble ($g\ m^{-2}\ yr^{-1}$)	Thatch ($g\ m^{-2}\ yr^{-1}$)	Moss ($g\ m^{-2}\ yr^{-1}$)	ANPP ($g\ m^{-2}\ yr^{-1}$)
2006	248 (47)	148 (15)	135 (24)	44 (13)	575 (70)
2007	144 (24)	133 (15)	190 (21)	73 (28)	541 (40)

Table 5. Comparison of urban grassland productivity measurements [ANPP – aboveground net primary productivity, TNPP – aboveground + root net primary productivity, *estimated value]

Source	Number of Sites	ANPP ($g\ m^{-2}\ yr^{-1}$)	TNPP ($g\ m^{-2}\ yr^{-1}$)	ANPP ($gC\ m^{-2}\ yr^{-1}$)	Study Region
This Study	33	82-1311	95-1523*	43-640	Maryland
Falk 1976	1	-	1650	-	California
Falk 1980	2	-	1020	-	Maryland
Qian et al. 2003	12	-	1260	-	Colorado
Golubiewski 2006	53	80-1228	-	-	Colorado
Kaye et al. 2005	3	-	-	383	Colorado

Figure Legends:

Figure 1. Study sites (n=33) were located within Baltimore City and Baltimore County Maryland. Neighborhoods used for study site selection are outlined with study sites represented as circles within the neighborhood boundaries.

Figure 2. Percent contribution of urban grassland components to aboveground productivity; comparison of paired study sites (n=21). [Clippings – total clipping biomass; stubble – stubble production, thatch – thatch production, moss – moss production].

Figure 3. Daily precipitation (cm) during the growing season (April 1-November 15) for Baltimore, Maryland region (weatherunderground historical data –plan to replace data with historical from NOAA…trying to think of a different way to graph precip/clipping relationship).

Figure 4. Relationship of soil and root respiration to total clipping productivity.

Figure 1. [*This figure will be redone to include an inset of where this is in region…other suggestions appreciated*]

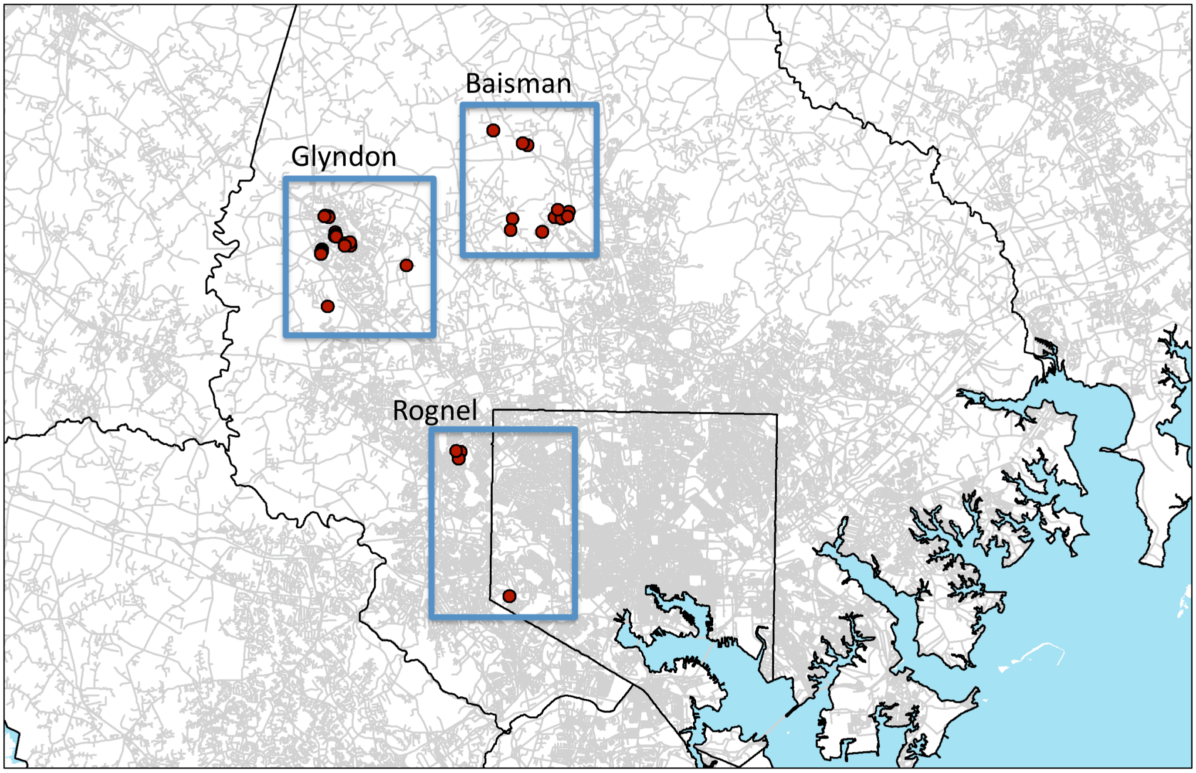


Figure 2.

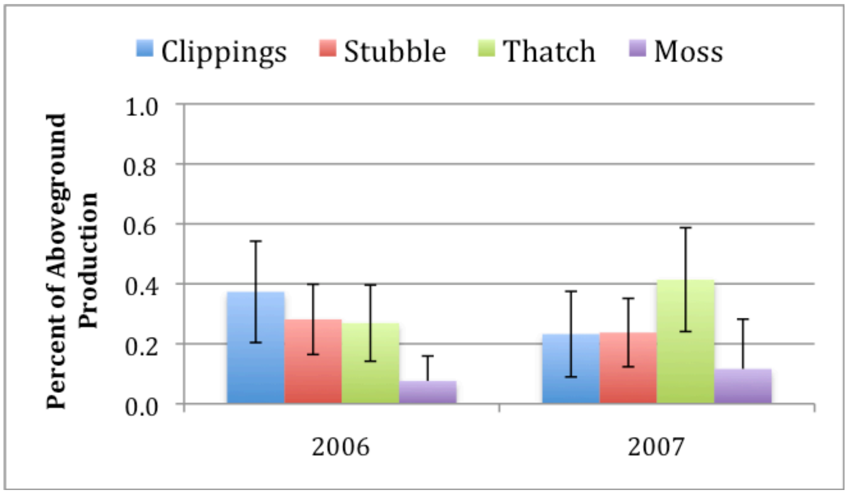


Figure 3. *Plan to replace data with historical from NOAA, currently from weatherunderground…Is this graph helpful or distracting? I am trying to think of a different way to depict precip/clipping relationship).*

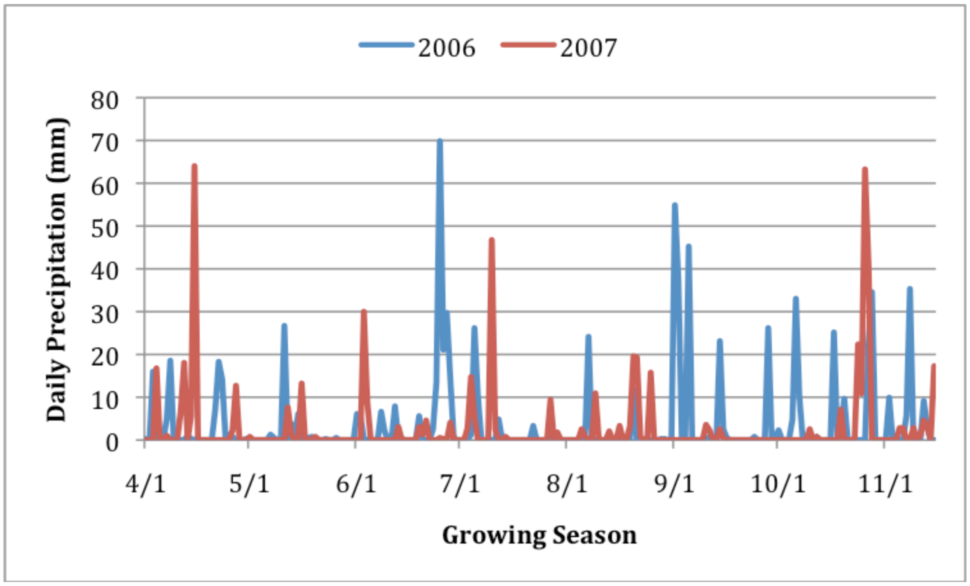
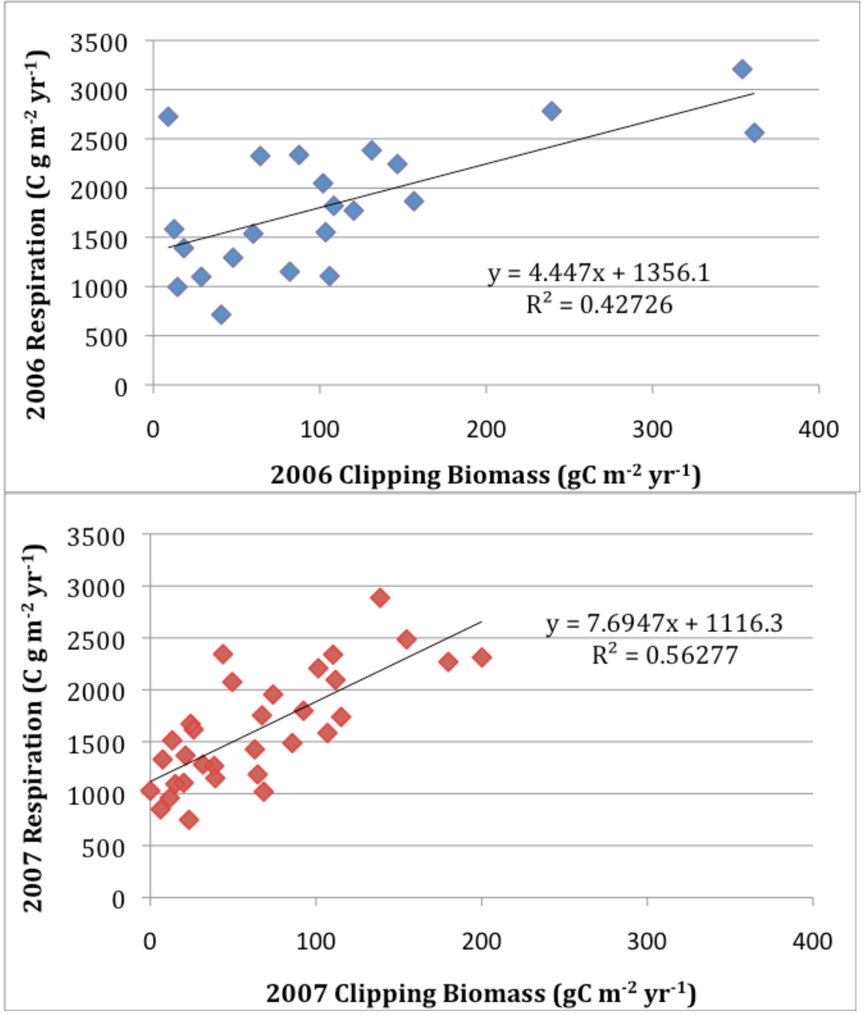


Figure 4.



2006 Respiration (C g m-2 yr-1)
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
2006 Clipping Biomass (gC m-2 yr-1)
y = 4.447x + 1356.1
R2 = 0.42726
2007 Respiration (C g m-2 yr-1)
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
2007 Clipping Biomass (gC m-2 yr-1)
y = 7.6947x + 1116.3
R2 = 0.56277