

**LINKING RESIDENTIAL DEVELOPMENT TO SOIL QUALITY: A FIELD
STUDY IN CHITTENDEN COUNTY, VERMONT**

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ABSTRACT

Urbanization has been found to alter soil properties and processes that can have important influences on critical ecological functions such as carbon, nitrogen, and phosphorus cycling. As urban areas continue to grow and expand, a better understanding of the impacts resulting from residential development and homeowner lawn management is important to quantify how nutrients behave in the urban environment. The main objectives of this study were to determine if soil quality differed in residential developments as a function of increasing time since development (lawn age), increasing development intensity (population density and average surrounding parcel size (APS)), and lawn management practices (current fertilizer use). Soil quality was defined on the basis of soil properties and processes that included: total carbon (TC) and nitrogen (TN) content, microbial biomass carbon (MBC) and nitrogen (MBN), soil respiration, potential nitrogen mineralization (PNM), and potential net nitrification (PNN). Sixty-five lawns were sampled from August and September of 2006 in Chittenden County, Vermont, USA.

Student t-test, Pearson Correlation analysis, and multivariate linear regressions were used to identify relationships with soil quality indicators and lawn age, urban intensity, fertilization, and natural soil properties. We found that characteristics of residential land use play a role in the ecological functioning of urban soil. Similar to previous research, our study identified a positive correlation with the age of the lawn to organic components of soil such as OM, TC, TN and biological microbial biomass across a broad sampling of sites. Lawn fertilization practices had significant effects on soil indicators in which, currently fertilized lawns (53%) had significantly lower soil respiration, TC, and OM ($p\text{-value} \leq 0.05$) and significantly higher PNM compared to lawns currently non-fertilized (47%). The results identified that homeowner management influenced the soil nutrient pools and may indicate that current fertilization can accelerate OM breakdown or currently fertilized soil may allocated less soil organic carbon belowground. Although we found urban intensity significantly influenced microbial biomass and PNN, it did not play a large role in explaining variance in the soil quality indicators. As development density captures multiple characteristics of the residential urban area, the density impact on lawn systems may be obscured with correlated factors. Additionally, urban density may not be the right predictor to capture the influence of development patterns in less urbanized areas like Chittenden County.

Through this study we can conclude that residential areas in Chittenden County, VT differ in soil quality with homeowner lawn management practices and temporal trends from development patterns. The identification of these individual factors of residential lawns can be used to characterize residential neighborhoods and identify how development (single age versus multi-age neighborhoods) and lawn management patterns interact in a watershed and implications they may have for retaining and exporting nutrients from the soil environment.

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CHAPTER 1: LITERATURE REVIEW

1.1. Introduction

As urban expansion continues and new homes sprawl across the landscape, an environment forms that is modified by the structure and intensity of land development. The process of constructing urban areas introduces new land sources (fill), reshapes the land, and creates impervious structures (Pouyat et al. 2003; Scharenbroch et al. 2005). The results of this development can alter the soil's environment where soil structure, organism composition, and chemical properties and process may be altered (Harris 1991). Within cities distinctive climates and resource inputs emerge with increased exposure to atmospheric and transportation contaminants and warmer climates from the cities' ability to retain heat (Groffman et al. 1995; Koerner and Klopatek 2002).

Urban landscapes may differ from preceding land use of agricultural fields and forestland, where management and patch extent was consistent on an expansive scale, by becoming a mixture of individual built patches. As landscapes are converted to residential parcels and divided into numerous smaller patches, the developed land use becomes a mosaic of patches micromanaged by individual homeowners. The management practices of the household can be variable from individual to individual and are largely unregulated as compared to other land uses (Robbins and Birkenholtz 2003). Therefore the micromanagement of a residential lawn has the potential for significant impacts on soil characteristics and processes and it is important to quantify how all these changes may affect the environment and its ability to function.

Urban ecology is an expanding field and provides important characterization of the effects urban expansion has on soil and water processes. This review summarizes a growing body of literature published in the last twenty years on the effect of urbanization to soil ecosystems. This review will focus on: 1) comparisons of soil properties and processes among urban and non-urban areas, with a particular focus on carbon and nitrogen cycling; 2) changes to soil characteristics and function from residential lawn construction; 3) role of fertilization and residential homeowner management on soil systems; and 4) a framework for investigating impacts to soil health in urban areas. The review will conclude with a summary of the scope and objectives of the research.

1.2. Anthropogenic Influence on Soil Dynamics

Anthropogenic activities have had numerous impacts on nitrogen (N), carbon (C), and phosphorus (P) cycles in urban areas. Industrial energy production has caused atmospheric changes such as photochemical ozone “smog” and acid precipitation, increased fossil fuel use has raised levels of atmospheric carbon dioxide (CO₂), production and application of industrial fertilizers has altered soil and atmospheric N pools, and runoff from agricultural and urban areas has contaminated surface and groundwater resources with nitrate (NO₃⁻) and P (Bennett 2003; Jaffe 2000; Koerner and Klopatek 2002; Pulford 1991; Robbins and Birkenholtz 2003; Vitousek et al. 1997). Cycles of N-fixation and denitrification have also been heavily influenced by anthropogenic activities resulting in an increase in the amount of N input into soil and cause elevated emissions and concentrations of N to the atmosphere (Jaffe 2000;

Schlesinger 1997). To identify impacts that anthropogenic activities can have on soil processes many researchers use a gradient analysis. Sampling along an urban to rural gradient quantifies changes in soil ecosystem processes and their functions in relation to decreasing degrees of urbanization. McDonnell et al. (1997) synthesized research on one such gradient from highly urbanized Bronx, NY out to a rural county in Connecticut. This gradient, as expected, portrayed a linear trend where human population density, traffic volume, and percent of urban development declined as distance from urban center increased. They note however that effects of urbanization on the soil ecosystem are complex and include factors such as shifts in soil organisms, climate, and atmospheric conditions as well as the distance from the urban core (McDonnell et al. 1997).

1.2.1. Urban to Rural Land Use Gradient

Several studies have employed urban gradients to compare impacts of urbanization on forest stands along an urban to rural land use gradient and identified that soil physical and chemical properties differed significantly along this gradient (Baxter et al. 2002; Pouyat and Turechek 2001; Zhu and Carreiro 2004a). Pouyat et al. (1995) found urban forest soils corresponded to higher concentrations of heavy metals (copper (Cu), nickel (Ni), lead (Pb)) and base cations (calcium (Ca), magnesium (Mg), potassium (K)), high total soluble salt concentrations, high organic matter (OM) and total N and soil acidity than rural forest soils. Developed soils have been found to have increased bulk density, higher temperatures, and altered soil moisture such as lower water tables (Groffman et al. 2002; Mullins 1991; Law et al. 2004). These differences in urban soil environments can alter soil functions in which soil with higher bulk density can decrease

the availability of OM for microbial processing and reduced soil moisture can impact soil fauna that need anaerobic conditions for denitrification (Groffman et al. 2002). Since anthropogenic activities have direct and indirect impacts on the environment, distinctions have also been made from comparisons between urban land uses. For example, Baxter et al. (2002) did not find significant differences in soil pH among urban and rural forest stands. However pH significantly distinguished urban residential areas from other turfgrass land uses by having a lower pH (more acidic) and higher aluminum (Al) concentrations (Pouyat et al. 2007). Furthermore soil in turf covered urban land use differed from urban forest stands due to higher concentrations of P, K, and increased bulk densities in turf sites (Pouyat et al. 2007).

1.2.2. Soil Carbon and Nitrogen Dynamics

A well studied process in the soil is the activity of heterotrophic microbes and their role in soil ecosystems of decomposing and mineralizing organic compounds (Figure 1.1.). The senescence of aboveground plant material, root turnover, and root exudates contribute to the OM layer both at the soil's surface and within the soil. Microbial mediated processes breakdown or decompose the OM and in the process microorganisms assimilate C and N from the OM as biomass (Robertson and Groffman 2007). As the microbes respire they release C into the soil atmosphere as CO₂. Once microbes have met their metabolic needs, excess N is released into the soil system as ammonium (NH₄⁺) in a process called N mineralization. One key fate and an important process in soil for NH₄⁺ is nitrification in which NH₄-N is oxidized by microorganisms and converted to nitrite (NO₂⁻) then NO₃⁻ (Pulford 1991; Robertson et al. 1999). Bacteria

in typical aerobic soil transform most of the available $\text{NH}_4\text{-N}$ by these processes so that NO_3^- is usually the dominant form of N available for uptake by plants and other microbes (Jaffe 2000). Both forms of inorganic N (NH_4^+ and NO_3^-) have the fate of immobilization by microbial populations and uptake by plants however inorganic N can be released into the atmosphere as N gas from volatilization of NH_4^+ and denitrification of NO_3^- . Another fate, that is a cause of concern due to pollution of groundwater and streams, is leaching of $\text{NO}_3\text{-N}$ from soil. As microbial activities are a primary mechanism for soil nutrient cycling, identifying the present status of microbial processes and the C and N dynamics in soil can provide an indication of the overall functioning or health of the soil ecosystem (Turco et al. 1994).

1.2.3. Carbon Dynamics in Urban Impacted Soils

The soil C pool is composed of the system's net primary productivity in which plants contribute to C pools through root exudates, root turnover, and senesced plant material or litter and soil fauna which aid in decomposing available OM and redistributing soil C (Horwath 2007; Pouyat et al. 2002). In natural soils the soil organic carbon (SOC) can be influenced by characteristics of the soil environment such as soil temperature, moisture, and texture as well as inputs to soil such as the C:N ratio of litter or the litter quality (Bandaranayake et al. 2003; Pouyat et al. 2006). In urban soils physical disturbance from construction, exotic plants, and chemical inputs from land management can directly impact soil C pools; while C pools are indirectly affected by local climate fluctuations, atmospheric deposition of contaminants, altered soil community, and soil hydrophobicity (Carreiro et al. 1999; Pouyat et al. 2002; Pouyat et

al. 2003; Pouyat et al. 2006). The overall effect of urbanization on soil C is uncertain as there is a small pool of available data making broad generalizations of C trends difficult.

Carreiro et al. (1999) conducted a temperature and moisture controlled laboratory experiment, and observed that leaf litter from rural forest stands supported more microbial biomass and faster litter decomposition than suburban and urban forest stands respectively. As urban litter exhibited slower decomposition after accounting for site differences that would influence decomposition rates, such as temperature fluctuation, it was then implied that urban stands had reduced litter quality meaning it was less mineralizable and harder for microorganisms to decompose. This reduction in litter quality is thought to occur from increased exposure to ozone and atmospheric contaminants in urban areas that alter the nutrient inputs to plants, subsequently reducing the quality of plant litter to urban forested stands compared to rural stands (Carreiro et al. 1999).

Pouyat et al. (2002) found urbanization altered SOC pools, in which urban forest soils containing high abundances of non-native earthworms had significantly higher surface mineral soil C densities than in suburban and rural soils that were less impacted by earthworms. A subsequent comparison of soils where earthworms are present (mull) and absent (mor) found C densities in mull surface mineral soil was significantly higher and mull forest floor significantly lower than mor soils in both categories (Pouyat et al. 2002). As no significant difference was found in total C density between these comparisons, the results indicate that the abundance of earthworms in urban stands redistribute organic C from OM deeper into the soil.

Continued research on litter decomposition supports these explanations of altered nutrient structure and influences of urban impacted environments that create SOC differences. A litter transplant study conducted in the field, along this same urban gradient, found rural litter decomposed faster regardless of whether it was placed in an urban or rural forest stand (Pouyat and Carreiro 2003). Rural litter in urban stands also had a higher net release of N coinciding with other's findings of increased mineralizable or labile N in rural litter (Carreiro et al. 1999; Pouyat and Carreiro 2003). Differences were not found in mass loss and N dynamics of urban, suburban, and rural litter when decomposed in their originating stand revealing that all the forest stands had factors present that affected decay rates (Pouyat and Carreiro 2003). This study and others identified environmental conditions along this gradient that influenced these rates such as increased soil temperatures and earthworm fragmentation of OM in urban forest stands, and cooler temperatures and increased microbial biomass leading to higher mineralization in rural forest stands (Groffman et al. 1995; Pouyat and Carreiro 2003; Zhu and Carreiro 2004b).

The density of C in soil also fluctuates among urban land use types. Pouyat et al. (2002) compared SOC densities from multiple studies and concluded that variation in C densities between cities was lower than the variation among different land use types. As urban lawns receive management inputs (fertilizer and irrigation), have a lack of soil disturbance, and a long growing season they have been found to have higher C densities and organic C than other urban and non-urban land use types (Kaye et al. 2005; Pouyat et al. 2003; Pouyat et al. 2006).

Urbanization can also influence the amount of C in the atmosphere. Koerner and Klopatek (2002) estimated CO₂ emissions in Phoenix, Arizona from anthropogenic sources including vehicles, airplanes, power plant emissions, and human respiration and found automobiles produced the highest amount of CO₂ per year. Soil respiration was the second largest contributor to CO₂ emissions with higher rates of CO₂ efflux from managed lawns, golf courses, and agricultural land that were irrigated than the efflux from surrounding desert or un-managed land (Koerner and Klopatek 2002). Fossil fuel emissions and other atmospheric pollutants like ozone may change the source of carbon to urban soils. Pollutants can produce hydrophobic soil and alter plant tissue composition; these changes may lead to lower microbial activity because of unavailable C, reduced soil moisture, and lower litter quality (Beyer et al. 1995; White and McDonnell 1988).

These studies demonstrate that a combination of interrelated variables explain changes that occur to C patterns in soil. Understanding how urbanization impacts C dynamics can have implications for issues like rising atmospheric CO₂. Turfgrass may be able to sequester C from the atmosphere by absorbing more CO₂ than it releases (Bandaranayake et al. 2003). But before we can reliably determine if turfgrass is a net sink for C, information is needed to better understand impacts to C pools and processes from development and anthropogenic activities.

1.2.4. Nitrogen Dynamics in Urban Impacted Soils

Several investigators have found that the N cycle is also altered in urban soil environments compared to non-urban areas. Urban forest stands, with acidic soils, had

increased NO_3^- -N concentrations and net nitrification rates compared to the rural soils and were found to support autotrophic microbes (Baxter et al 2002; Zhu and Carreiro 1999; Zhu and Carreiro 2004a). Zhu and Carreiro (1999) amended these rural forest stands with NH_4^+ to encourage nitrification; however the amendment only stimulated N mineralization and not nitrification rates. Therefore, this difference in NO_3^- among urban and rural forest stands was not explained simply by rural stands having reduced NH_4^+ concentrations limiting the nitrification process. A comparison of forest stands in the same region identified an opposing trend in which soil samples from an urban forest site had lower rates of nitrification than measurements at a rural site and the response was thought to be limited by low levels of NH_4^+ (White and McDonnell 1988). The response of N mineralization processes with urbanization is unclear as researchers have concluded that urban forest stands have not significantly differed from rural stands in N mineralization and NH_4 -N concentrations (Baxter et al. 2002; Zhu and Carreiro 1999), have shown decreased N mineralization (White and McDonnell 1988) and increased mineralization rates (Zhu and Carreiro 2004a). Illustrating this point, Pouyat and Turechek (2001) conducted a soil core transplant study in which rural soil cores were transplanted into urban soils to identify if the higher soil temperatures of urban soils would stimulate microbial processing of N; however no statistically significant differences were found in N rates.

Hope et al. (2005) found land management and socioeconomic status were stronger predictors of NO_3^- and NH_4^+ concentrations in an urbanized arid soil environment compared to natural soil properties. Areas characterized by increased

population density, households with higher per capita income, lower amounts of impervious surface, and low irrigation rates were more likely to have high NO_3^- whereas NH_4^+ was higher with decreased population densities, lower percent lawn cover, and increased irrigation (Hope et al. 2005). They attributed positive relationships between NO_3^- with population density and per capita income to differences in fertilization practices on the urban sites. In contrast, N processes on non-urban areas or desert sites were predicted best by soil physical properties (clay content) and patch size (landscape features) (Hope et al. 2005).

Potential N measurements can vary with the season, soil pH, vegetation type, heavy metal content and available C in the soil, disturbance of the surface soil, as well as measurement method (Munster et al. 2006; White and McDonnell 1988). Both urban and rural soil environments have been found to display typical seasonal patterns in which increased N mineralization and $\text{NH}_4\text{-N}$ concentrations occur in the summer corresponding to peak plant demand and uptake (Zhu and Carreiro 2004a). However, Zhu and Carreiro (2004a) found urban areas had an earlier peak in N mineralization rates than rural areas possibly due to the urban heat island effect in which warmer air temperatures occurring in cities warmed the soil up earlier in the season compared to soil in rural areas. A divergence in timing of peak nutrient availability to plant uptake in urban settings may not only influence the accessibility of nutrients to plants but may cause an elevated loss of nutrients from the soil. Baxter et al. (2002) did an analysis of plant uptake and demand for N and P on red oak (*Quercus rubra*) seedlings to identify if nutrient resources and availability to plants were impacted by urbanization. They

concluded that urban forest stands had lower plant available P and to a lesser extent N compared to rural stands, with low levels of N present in the seedling tissue at urban sites (Baxter et al. 2002).

Shifts in C and N processes from urbanization can be explained by several hypotheses that relate environmental conditions and anthropogenic impacts including:

- Increased exposure to N deposition, atmospheric pollution (ozone, SO_x, NO_x), heavy metals, and fossil fuel emissions in urban areas that lead to a reduction in litter quality, changes in soil available nutrients, and soil hydrophobicity (Carreiro et al. 1999; Beyer et al. 1995; White and McDonnell 1988).
- The urban heat island effect alters rates and seasonal timing of soil processes like decomposition of OM and N mineralization (Groffman et al. 1995; Zhu and Carreiro 2004a).
- Presence of invasive species can shift the structure of organic horizons and nutrient resources in urban soils. High abundances of non-native earthworms in urban soils changed SOC pools from labile to more recalcitrant and increased nitrification rates from soil mixing compared to rural soils with no earthworms present (Baxter et al 2002; Zhu and Carreiro 1999; Zhu and Carreiro 2004a).
- Anthropogenic inputs (fertilizer and irrigation), long growing seasons, and little disturbance after development in turfgrass can increase the amount of C sequestered in urban soil (Kaye et al. 2005; Pouyat et al. 2003; Pouyat et al. 2006).

Several of these hypotheses can be specific effects of the particular study region but the essential end result of these studies is the realization that the natural and human effects from urban areas are highly related in explaining these relationships.

1.2.5. Phosphorus Dynamics in Urban Impacted Soils

Phosphorus is commonly applied to soil in fertilizer and excess P not utilized by plants remains in the soil where concentrations can continue to build up (Foster et al. 2003). The P stored in soils is a concern as P lost from soil systems either by transport in surface runoff from fertilized soils or erosion of soil containing high P concentrations, are actions that pose a threat to the quality of water resources (Bennett et al. 2001; Easton et al. 2007).

Soil extractable P concentrations from human impacted landscapes, such as lawns and agricultural fields, have a higher probability that extractable P concentrations in these land use types will be greater than 30 mg P kg⁻¹ (Bray-1) compared to prairie soils (Bennett et al. 2004). As P levels exceeding this concentration reach a point where plants may not respond to additional P inputs (Bennett et al. 2004), the presence of high P concentrations do not enable further benefits to soil processes. To identify if soil P concentrations are related to historical land use and the intensity of land management, Bennett (2003) used an urban to rural gradient to predict extractable P concentrations in an urbanizing agricultural watershed. She expected to find lower P concentrations in the lawns of older urban areas, slightly higher P concentrations in newer developments or areas most recently converted from agricultural land use, and the highest P concentrations in the surrounding agricultural areas. The results of the analysis showed that 37% of the

variation was explained by the urban-rural gradient, topography, land use, land cover, manure use, and soil type. However the urban-rural gradient alone was not identified as a good predictor of extractable P, by explaining only ~3% of the variation in extractable P concentrations (Bennett 2003). Some of the explanations offered by Bennett (2003) as to why only a third of the variation in the dataset was accounted for include variability of soil extractable P measurements and potential legacy effects of P.

Phosphorus accumulates in the soil with continued fertilization applications and it is unknown how long it takes for extractable P levels to decrease once fertilization practices are stopped. Soil test P or extractable P in the topsoil has been found to relate to dissolved reactive P (DRP) concentrations in surface runoff (McDowell and Sharpley 2002; Watson et al. 2007). Watson et al. (2007) found grasslands that were fertilized with N and P for 6 years accumulated more P in the soil and plant tissue than the control grassland receiving N fertilizer alone. As expected, P in overland flow and land drainage increased with higher application rates of P and none of the grasslands sites were found to be P deficient (Watson et al. 2007). However, after 6 years without P inputs, the control grassland showed little change in the amount of P in soil (Olsen-P) or DRP and total P concentrations in overland flow and land drainage (Watson et al. 2007). In addition, the control plots were still exporting P levels high enough (greater than $35 \mu\text{g P L}^{-1}$) to trigger eutrophication in lakes.

Little research is available on what the potential impact of excessive P concentrations in urban systems can mean for the health of the lawn and the quality of local water bodies (Bennett et al. 2001). As Watson et al. (2007) observed, six years was

not long enough to see differences to P levels of previously managed (fertilized) soils. Available research does show that human dominated sites (agriculture and turfgrass) are more homogeneous in P concentrations compared to non-managed sites (natural prairie) but that differences in management intensity can produce higher variance among these sites making P concentrations hard to predict (Bennett 2004; Watson et al. 2007).

1.3. Impacts of the land development process

Conversion of land from agricultural and forest to urban and suburban uses is a steadily increasing trend and a factor of urban sprawl. In the conversion of land to residential communities many changes can take place to the land and soil that influence the soil's natural characteristics and functions. The variability present in urban soil properties is thought to be a factor of the initial physical disturbance from land developments, as the development process has lasting impacts on soil's structure, stability, and nutrient cycling capabilities. When building residential areas heavy machinery compacts soil during construction, fill can be introduced to replace or be mixed with the present soil, and the pervious land area is reduced by inclusion of impervious surfaces such as building footprints and pavement. Potential outcomes from this disturbance include compaction and surface crust formation, impeded percolation and aeration, loss of OM from surface exposure, as well as modified nutrient cycling and soil organism regimes (Harris 1991; Mullins 1991). Additionally, new developments receive high rates of fertilization shortly after construction for the establishment of turfgrass, however the modified conditions of the soil (compaction) and little ground

cover during this period with high fertilizer application rates increase fertilizer loss in runoff from the system (Easton and Petrovic 2004; Law et al. 2004).

Impacts to soil in urban environments depend on the inherent physical properties of the soil (particle size distribution), applied land use (recreational fields that require management and have high public use; Mullins 1991), and historical land use (legacy effects from agricultural management practices). The particle size density can be an important measure of the soil in urban areas as it will be less affected by management at the soil's surface. The texture of soil and its use can impact other soil properties such as porosity, structural stability, saturated hydraulic conductivity, and carbon content that can alter the infiltration and drainage of water as well as soil aeration (Mullins 1991). These changes in turn impact the amount of runoff from the soil as well as diffusion and transport of gasses and liquids within the soil environment (Mullins 1991). This point is supported by studies done on the hydrologic cycles of residential lawns in which the most influential factors that altered infiltration rates included discontinuities in the soil's texture and compaction that may have been created during home and lawn construction (Kelling and Peterson 1975; Hamilton and Waddington 1999). Compaction can be seen in high-use urban areas such as the Mall in Washington D.C. and New York's Central Park where bulk density values ranged well above 1.6 t m^{-3} , a level that can impede root growth (Mullin 1991).

1.3.1. Relationship with lawn establishment

Relationships have been observed with several soil properties and time (years) since construction of the urban development. Post-development, soils can have reduced

soil quality for plant growth and water movement but over time these conditions have been found to improve as the soil recovers from disturbance. Therefore, lawn age correlates with several lawn and soil characteristics.

Petrovic (1990) reported that total organic N (TN) in the top 0-10 cm of soil increased with age and the greatest change in soil N occurred within the first 10 years of lawn establishment and then reached an asymptote after 20 years. Law et al. (2004) found a similar trend in which lawns with lower N content were associated with subdivisions less than 10 years old. The trend of increased nutrient content with lawn age has also been observed with total organic C (TC) (Golubiewski 2006) and soil OM levels, Figure 1.2. (Munster et al. 2006; Scharenbroch et al. 2005). Rate of soil C accumulation in turf systems have been found to accrue at an average rate of 0.9-1.2 Mg ha⁻¹ yr⁻¹ on loam to clay loam soils during the first 30 to 40 years after establishment, Figure 1.3. (Bandaranayake et al. 2003; Qian and Follett 2002). However this rate is likely enhanced by management practices (fertilization and irrigation) as the rate of C accumulation in a grassland system after a disturbance was only 0.33 Mg ha⁻¹ yr⁻¹ (Qian and Follett 2002). Prior land use does influence the quantity of OM available post-development or the urbanized starting point, but prior land use does not prevent this pattern seen in accumulation of soil OM over time. For example, Qian and Follet (2002) identified SOC on golf course fairways less than 10-years old had 24% lower SOC if they were previously agricultural land than fairways constructed on native grasslands.

Scharenbroch et al. (2005) found younger residential sites (sites less than 10 years old) had higher bulk density and lower levels of microbial biomass than residential

sites greater than 50 years of age. Younger residential sites also had less available N (microbial biomass N and potential N mineralization) and lower potential soil C mineralization compared to older sites (Scharenbroch et al. 2005).

Beyer et al. (1995) reported temporal changes in the composition of urban soil OM pools, in which soils 10-20 years old were dominated by litter compounds and older soils (>100 yrs) with higher humic compounds. Due to this redistribution, younger soils had more available sources of OM for microbial activity from the litter compounds compared to the humic compounds in older soils that are less available to soil microorganisms. In addition, Beyer et al. (1995) observed that all urban soils had OM that was characterized by low levels of recalcitrant fractions of lipids and waxes and the mobile fulvic acid in comparison with natural mineral soils.

This temporal trend of nutrient build-up in soil post-disturbance has also been observed in grassland soils. Hassink (1994a) found TC and TN content of soils converted from arable land to grassland in the Netherlands were significantly higher in 10-year old grassland soils compared to lower nutrient levels in grasslands 1-3 years old. Soil respiration and N mineralization were also higher in older grasslands, with this pattern occurring on both loam and sandy soils (Hassink, 1994a). However, Accoe et al. (2004) found gross immobilization of N by microbial activity may increase with time in grasslands as the availability of C and OM increase in both the 0-10 cm and 10-20 cm of the surface soil; this was reflected by strong positive correlations between gross N mineralization (nitrification and immobilization) with TC and TN. Accoe et al. (2004) also found that the TC and TN content in the 0-10 cm soil layer increased with the age of

grasslands that had not been disturbed for 6, 14 and 50 years since conversion from arable land. In addition, the labile pool of SOM accumulated rapidly after disturbance such that 14-year old grasslands were found to have twice the amount of labile SOM as 6-year old grassland soils.

1.4. Residential lawn management

Lawns are common features within residential areas and as lawn area increases, with the rapid rate of land development, the amount of chemicals applied to lawns also increase. Milesi et al. (2005) projected turfgrass covers over 160,000 km² of the US, equating to nearly 2.0% of the total land area in the continental US of which residential lawns could account for half. Robbins and Birkenholtz (2003) reported that 84% of households in the US use fertilizers and 64% apply pesticides to their lawn. With the perspective that urban land area is estimated to cover 3-5% of the US (Milesi et al. 2005), residential lawns then equate to roughly 20-30% of urbanized areas (Ludowski et al. 2005; Milesi et al. 2005; NRCS 2007). As the majority of lawns are fertilized this estimate of turfgrass and its management becomes an influential factor in determining nutrient balance in the lawn and surrounding urban area.

1.4.1. Impacts of Fertilization on Soil

Through the application of fertilizer, humans have doubled the rate of reactive N into the terrestrial biogeochemical cycle. Fertilization can increase concentrations of volatile ammonia (NH₃) in soils, increase microbial processing of fixed N, impact water quality from NO₃⁻ loads in runoff, and can ultimately increase emissions of N gases

(Galloway et al. 1995; Vitousek 1997). In turfgrass systems, fertilization and irrigation provide benefits to plants by elevating the productivity of the lawn which leads to increases in soil OM and SOC from above- and below-ground biomass turnover (Haynes and Naudi 1998; Qian and Follett 2002). This recycling of biomass in the soil provides labile C that can improve soil aggregation and infiltration, microbial activity, and decrease bulk density (Bronick and Lal 2005; Haynes and Naudi 1998). Because of this process, fertilizer applications and irrigation on turf systems can produce higher C sequestration rates during the turf establishment period (Qian and Follett 2002).

Fertilization practices in a study by Kaye et al. (2005) found that net primary productivity was highest in corn sites followed by urban sites and lowest on the unfertilized shortgrass steppe and wheat sites. They found soil respiration in urban sites increased earlier in the spring and maintained a higher respiration rate through the summer than the other sites, which was attributed to consistent soil moisture from irrigation and not from the urban heat island effect or natural precipitation (Kaye et al. 2005). Fertilized sites had higher percent N concentrations in the plant tissue (corn and lawn) versus unfertilized wheat and urban lawns allocated more C belowground and surface C storage than the agricultural land uses or unfertilized shortgrass steppe (Kaye et al. 2005). To measure effects of fertilization and irrigation practices on microbial biomass, Kaye et al. (2005) used a phospholipid fatty acid analysis and found total fungal and bacterial biomass were twice as great at urban sites than the other three land uses. Although fertilization provides benefits for plant productivity and soil nutrient pools,

avoidance of an imbalance to soil nutrients such as too much mineralizable N is a key factor for ecosystem health.

1.4.2. Importance of proper management

It has been shown in studies that when good fertilization practices and proper turf management were used turfgrass was not a significant source of nutrient loss to the environment (Easton and Petrovic 2004; Gross et al. 1990). However, when former agricultural land is converted to residential land use the amount of leaching or groundwater pollution from soil may be similar if proper land management practices are not followed (Gold et al. 1990). Leaching of fertilizer N applied to turfgrass was found to be associated with the following factors: amount and timing of application, species of turfgrass, quantity and time of watering, soil infiltration rate, N fertilizer source or type (urea vs. nitrate, pellets vs. liquid, slow-release), vegetation density, soil microbial activity, site specific characteristics, as well as lawn age (Easton and Petrovic 2004; Gold et al. 1990; Liu et al. 1997; Osmond and Hardy 2004; Petrovic 1990). The most influential variables were the rate and timing of the fertilizer application, grass species, irrigation practices, and soil infiltration rate.

For example, turfgrass species have different $\text{NO}_3\text{-N}$ absorption efficiencies that have a strong influence on the amount of $\text{NO}_3\text{-N}$ leaching from soil (Liu et al 1997). Turfgrass species with a high $\text{NO}_3\text{-N}$ absorption efficiency can significantly reduce NO_3^- leaching. This can be an important factor to consider when timing fertilization applications where species such as Kentucky bluegrass were found to have a higher

leaching potential than tall fescue likely due to differences in species life histories and periods of growth (Liu et al. 1997).

Once established, turfgrass should reduce sediment loss and slow the velocity of runoff allowing for increased infiltration into soil (Gross et al. 1990). In addition, soil with a higher permeability contributes less fertilizer as surface runoff even when fertilization rates are increased because there is a greater opportunity for processing of the nutrients deeper in the soil as the fertilizer infiltrates (Keeling and Peterson 1975).

Law et al. (2004) surveyed homeowners in two urban watersheds in Baltimore County, Maryland to identify how fertilizer application can alter the urban N cycle and found that the amount of fertilizer was correlated to factors including age of the development, soil bulk density and soil N content. A significant relationship existed between median age the house was built by subdivision and the annual amount of N applied to the lawn (Figure 1.4.). Based on these findings and results from soil analysis showing lower N and C contents with newer developments (less than 10 years old), the authors hypothesized that homeowners in the newer developments applied more fertilizer to their lawns for lawn establishment as well as to improve the reduced quality of soil from recent construction (Law et al. 2004).

Results of a survey done by Osmond and Hardy (2004) showed that homeowners were in some cases over-watering their lawn, improperly using fertilizer (amount, timing, and incorrect blend for their lawn), and were not clearing fertilizer from impervious surfaces. These points were reinforced by Robbins et al. (2001) who found that many homeowners were unaware of the type of chemicals they apply on their lawn

and what the chemicals contained. Law et al. (2004) found that fertilizer application rates varied spatially and were influenced by the quality of the soil. Raising the awareness of individual homeowners on proper management practices such as fertilizer and irrigation recommendations specific to a homeowner's grass species and current soil nutrient status is an important action for reducing potential anthropogenic impacts from residential areas.

1.5. Soil Quality as a Framework for Ecosystem Health

As discussed above soil functions can have both positive and negative outcomes for other components of an ecosystem. The quality of soil is often defined in terms of functions and positive feedbacks that are provided by the soil's physical, chemical, and biological attributes. Soil with "good" tilth and fertility provides a medium for plant growth and soil with "good" structure and OM can store and distribute water as well as help to degrade environmental pollutants by the chemical, microbial, and sorption properties of soil (Beck et al. 2005; Doran and Parkin 1994; Karlen and Stott 1994). For instance, water carrying inputs from anthropogenic activities (fertilizer, septic effluent, pet waste, and road salt) infiltrates into soil and passes through a soil interface in which these inputs can be altered by cation exchange, sorption, oxidation/reduction reactions, precipitation/dissolution, denitrification or other microbial processes (Thomas 2000). However imbalances to the C and N cycle in soil can inhibit some of these changes from occurring such as a soil with low OM and a high C:N ratio can have reduced microbial

mediated processes thereby allowing pollutants to pass through the soil unchanged and contaminate natural resources like ground water.

Levels of soil quality can be defined by the stable natural features relating soil-forming factors and dynamic changes induced by soil management or disturbance (Doran and Parkin 1994). This identification of the present state of the soil will provide an indication of how that soil will function in the future. Doran and Parkin (1994) proposed a framework to assess the quality of agricultural soils that was based on agricultural productivity, performance, and sustainability. They list several criteria that soil measurements should meet to be an indicator of soil quality:

- “1. encompass ecosystem processes and relate to process oriented modeling;
 2. integrate soil physical, chemical and biological properties and processes;
 3. be accessible to many users and applicable to field conditions;
 4. be sensitive to variations in management and climate; and
 5. where possible, be components of existing soil data bases.”
- (Doran and Parkin 1994 p. 9)

Established physical, chemical, and biological soil parameters listed in Table 1.1 should be considered as indicators given that these methods have a literature base of reported values and will help to facilitate comparisons of studies by defining a standard for the types of measurements that should be collected in soil assessments.

The application of soil quality indicators to residential lawns can serve to identify baseline conditions of soil in residential areas and determine if urbanization characteristics influence the function of residential soils. Many of the potential soil quality indicators listed in Table 1.1 are established methods and can be found in the

literature for grassland, agricultural, and urbanized systems. Therefore these measurements can aid in comparisons to identify potential relationships between soil function and urbanization.

1.6. Gap Analysis

Observed trends along urbanized gradients provide evidence of anthropogenic influence on soil ecosystems where differences have been found between urban and rural environments with respect to $\text{NO}_3\text{-N}$ and heavy metal concentrations as well as soil OM (Beyer et al. 1995; Pouyat et al. 1995; Pouyat et al. 2002; Zhu and Carreiro 1999). Explanations for the cause of these differences are provided by a multitude of factors including atmospheric pollutants, presence of soil organisms, and available inputs of nutrients like litter quality from urban influenced environments (Baxter et al. 2002; Carreiro et al. 1999). Although a growing body of research exists with respect to urbanized gradients in highly impacted urban areas like New York City and Baltimore, Maryland; there are relatively few studies available that have taken this approach and applied it elsewhere to areas less impacted by urbanization. Additional research is needed to identify the potential influence development and anthropogenic activities have on soil in less influential urban areas that represent different development patterns, a less established urban area, and areas currently expanding.

Also the process of developing new land greatly modifies the structure of soil linking factors relating the lawn age or time since development to soil processes and functions like permeability and nutrient cycling. Although specific soil properties have

been shown to correlate to lawn age such as higher bulk density, increased runoff and lower levels of TC and TN on younger lawns (Easton and Petrovic 2004; Law et al. 2004; Scharenbroch et al. 2005), this relationship has not been explored extensively in urban residential environments or across multiple residential developments.

Furthermore, little information is available that addresses what a neighborhood with differing managing regimes per household means for impacts to the surrounding environment. Land management maybe a key factor of how residential soil may impact the neighborhood and watershed performance, however few studies have linked the homeowner's management behavior directly to the soil properties and processes occurring in the homeowner's lawn. Several of the key variables that affect available nutrients and leaching in soils are those that are also important in homeowner management like correct fertilization and irrigation practices (Gold et al. 1990; Liu et al. 1997). Information on impacts resulting from residential development and homeowner lawn care would help to quantify the affects that development has on important ecosystem functions such as delivery of non-point source pollution to receiving waters (Groffman et al. 2002; Nielson and Smith 2005). Certain biological and physical measures in the soil have been found to be affected by urban land management such as soil microbial biomass and soil OM (Kaye et al. 2005; Pouyat et al. 2003) but further explanation is warranted to understand homeowner management in the context of other influential urban parameters.

1.7. Scope and Research Goal

1.7.1. Research Application in Vermont

This research aims to address the above gaps in knowledge by conducting an extensive field study of residential lawn soils in Chittenden County, Vermont to determine the impacts of residential development on soils. While Chittenden County may not be a large metropolis, trends in land development in Chittenden County and the state of Vermont mirror those occurring across the US (Census 2007; NRCS 2007). The percentages of developed land increased (+31%) in Vermont from 1982-1997 that were close to double the increase in population (+17%) during 1980-1997 (Census 2007; NRCS 2007); exemplifying that the rate of land use change for urban development is increasing at a greater rate than population growth. In comparison Chittenden County, VT, home to approximately one-fourth of Vermont's residents, reflected a greater impact from urbanization in which land development increased by 47% and population increased by 24% during these time periods. These increases in developed land use for Chittenden County during 1982-1997 created shifts in the dominant land use types with a 19% decrease in percent agricultural with a small net increase in forestland (< 2%) (NRCS 2007).

Urbanization has continued to expand in VT and has lead to shifts in land use, as developed land increased an addition 9% from 1997 to 2003 a corresponding occurred to both percentages of agricultural (-7%) and forested (-9%) land (NRCS 2007). Due to these recent patterns of urbanization, Vermont provides an opportunity to study

residential soils in an actively urbanizing landscape. Furthermore few studies are available that quantify the impacts of urban expansion to soil systems in the Northeast.

The cycling of nutrients (C, N, and P) in soil is very dynamic and an imbalance of one of these nutrients can produce negative feedbacks for the soil system. For example, soils that have been impacted by urban pollution or degraded from construction (low organic components and high compaction) may support lower microbial populations in turn impacting the nutrient transformation services the microbes provide and potentially increasing the amount of pollutants (NO₃ and P) that get to our water resources. A better understanding of the impacts resulting from residential development and homeowner lawn management would provide important information regarding impacts to surrounding natural resources such as nutrient transport to Lake Champlain. This research will aid in identifying if fundamentally important soil processes, such N and C dynamics, in residential developments are affected by increasing urbanization in Chittenden County. By sampling residential lawns that vary in urban characteristics we will be able to test if specific anthropogenic influences can be identified at a broader scale than in previous research comparing selected neighborhoods.

This study utilizes a suite of soil parameters to quantify soil quality that include several measurements of chemical and physical parameters from Table 1.1. To identify the response of soil processes to urban influences, measurements that can detect recent disturbances need to be considered. For example, changes in soil TC and TN occur slowly and annual changes are generally small while soil microbial biomass has a relatively short turnover of less than 1 year (Hassink 1994b; Qian and Follett 2002; Rice

et al. 1996). Therefore, detectable changes due to anthropogenic activities such as fertilization and disturbance may be reflected earlier in the microbial biomass than differences to the recalcitrant pools, making microbial biomass a potentially responsive indicator to disturbance (Rice et al. 1996; Turco et al. 1994). As measurements of microbial biomass and N mineralization can be sensitive to seasonal variation these indicators were used to capture a snapshot characterization of the lawn and soil condition for comparative purposes and were not meant to be generalized over a broader timeframe than the season sampled.

1.7.2. Research Hypotheses

The goal of this research was to determine how residential development affects soil quality indicators in Chittenden County, Vermont. To address this goal a set of established physical, chemical, and biological soil measurements were employed as a framework to quantify soil quality in residential developments and to test whether urbanization significantly alters these key soil properties and processes. The following objectives and hypotheses were tested:

1. Objective: Determine how soil processes (potential N mineralization, potential net nitrification, and soil respiration) differ with increasing lawn age and urban density.
 - a. Residential soil processes will differ in respect to lawn age.
 - i. Hypothesis: Younger lawns will have reduced rates of potential N mineralization, potential net nitrification, and soil respiration compared to older lawns.

- b. Residential soil processes will differ in respect to urban density.
 - i. Hypothesis: Higher density residential sites will have decreased potential N mineralization and increased potential net nitrification rates compared to lower density residential soils.
- 2. Objective: Determine how soil properties (microbial biomass C and N, TC content, and TN content) differ with increasing lawn age and urban density.
 - a. Residential soil properties will differ in respect to lawn age.
 - i. Hypothesis: Younger lawns will have lower TC, TN, and microbial biomass compared to older lawns.
 - b. Residential soil properties will differ in respect to urban density.
 - i. Hypothesis: Higher density residential sites will have lower levels of TC, TN, and microbial biomass compared to lower density residential soils.
- 3. Objective: Determine if lawn management practices (fertilization) influence soil properties and processes.
 - a. Soil processes will be affected by differences in homeowner lawn management.
 - i. Hypothesis: Currently fertilized lawns will have greater C and N mineralization as well as microbial biomass compared to currently non-fertilized lawns.

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Table 1.1. Proposed soil measurements to be utilized as soil quality indicators (taken from Doran and Parkin 1994).

Soil Parameter	Methodology
PHYSICAL	
Soil Texture	Hydrometer method
Depth of soil and rooting	Soil coring or excavation
Soil bulk density and infiltration	Field determined using infiltration rings
Water holding capacity	Field determined after irrigation of rings
Water retention characteristics	Water content at 33 and 1500 kPa tension
Water Content	Gravimetric analysis; weight loss after 24hr at 105°C
Soil Temperature	Dial thermometer or hand temperature probe
CHEMICAL	
Total organic C and N content	Wet or dry combustion
pH	Field or lab determined
Electrical conductivity	Field or lab determined
Mineral N (NH ₄ ⁺ and NO ₃ ⁻), P, and K	Field or lab determined
BIOLOGICAL	
Microbial biomass C and N	Chloroform fumigation/incubation
Potentially mineralizable N	Anaerobic incubation
Soil respiration	Field or lab determined
Biomass C/Total organic C ratio	Calculated from other measures
Respiration/biomass ratio	Calculated from other measures

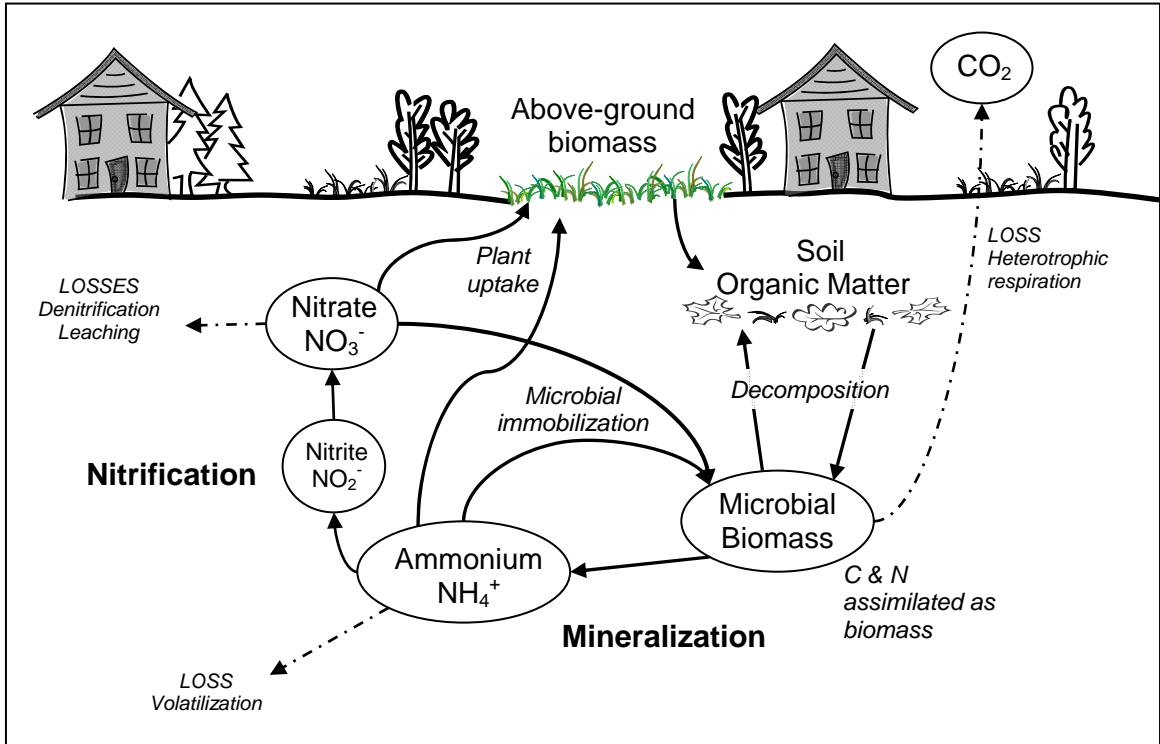


Figure 1.1. Role of heterotrophic microbes in mineralizing organic compounds (adapted from Brady and Weil 2002).

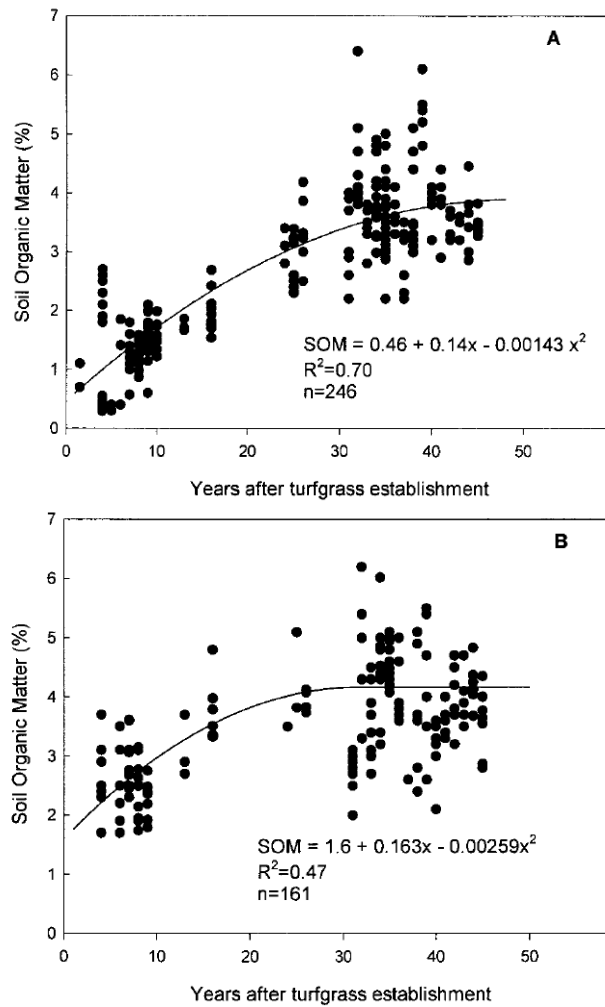


Figure 1.2. Build-up of SOM with time since turfgrass establishment of (A) putting greens (n=16) and (B) fairways (n=13) from soil testing of golf courses in Colorado (taken from Qian and Follett 2002)

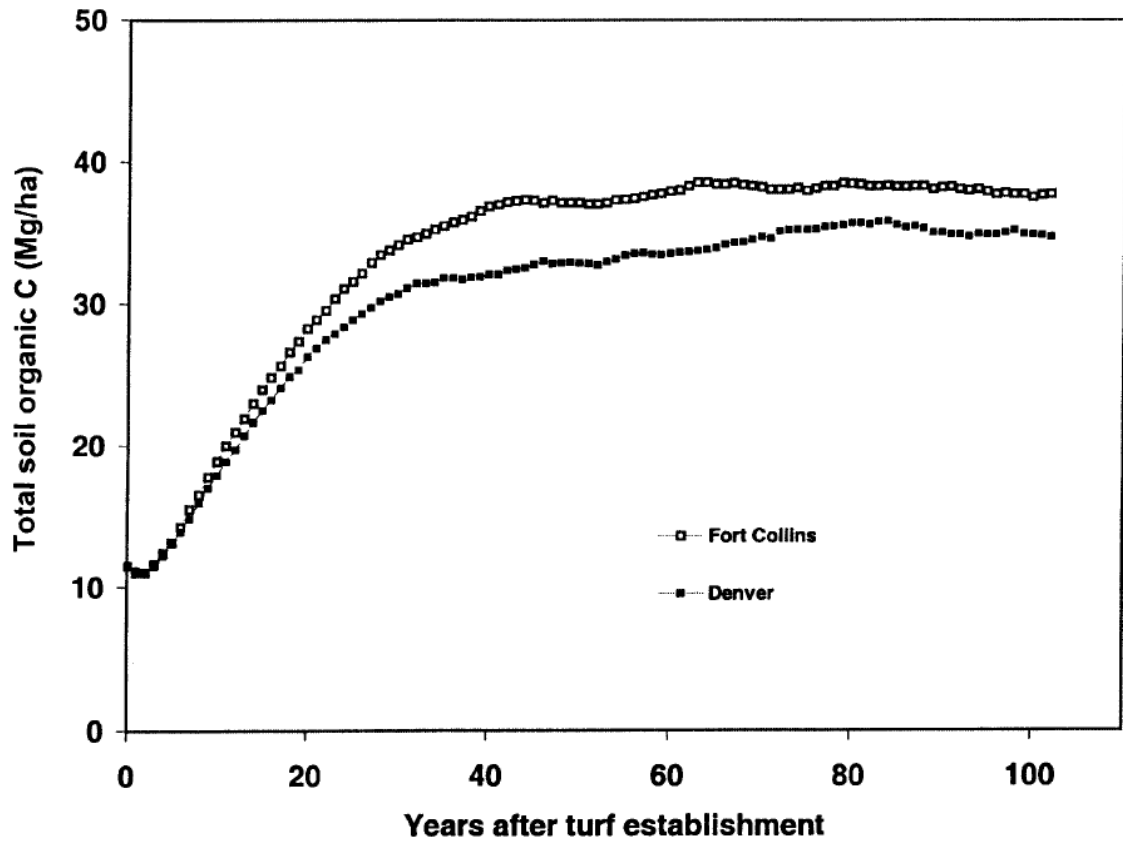


Figure 1.3. Modeled temporal increase in total soil organic C from putting green turf in Colorado using the Century model (taken from Bandaranayake et al. 2003)

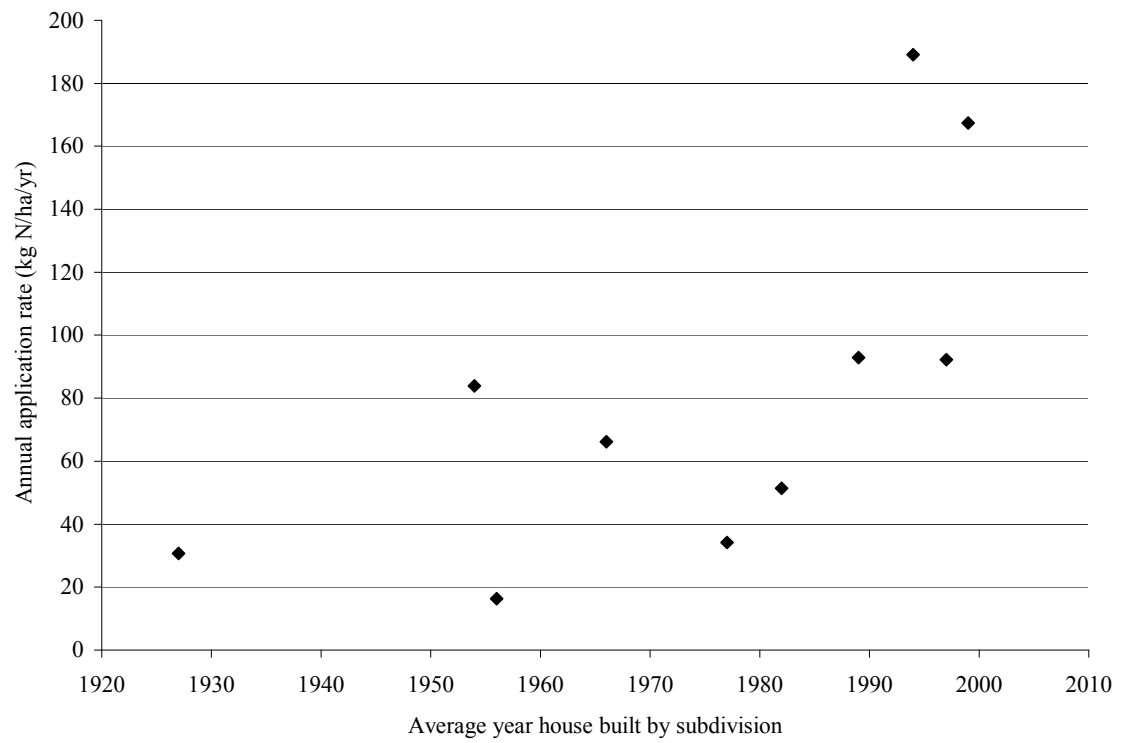


Figure 1.4. The average annual application rate of fertilizer as a function of the average lawn age or average year the house was built (taken from Law et al. 2004).

CHAPTER 2: CHANGES IN SOIL CHARACTERISTICS AND PROCESSES IN AN URBAN LANDSCAPE: LINKING DEVELOPMENT TO SOIL QUALITY

2.1. Introduction

The study of urbanization has become an important topic in ecology due to the rapid growth and expansion of urban areas. From 1982-1997 the percent of developed land use in the US increased by 34% which corresponded to a net decrease in agricultural land (-13%) and minimal change to forestland (NRCS 2007). However the total population in the US during 1980 to 1997 only increased by 18%, exemplifying that the rate of land use change for urban development is increasing at a greater rate than population growth (Census 2007; NRCS 2007). As agricultural and forested lands are converted to urban areas, the resulting land use is a complex arrangement of impervious areas and highly managed pervious areas including lawns. Milesi et al. (2005) estimated that turfgrass covers approximately 160,000 km² and equates to nearly 2% of the total land area in the continental US. Although this estimate includes all potential urban land use covered in turfgrass; residential lawns could account for half of this estimate (Milesi et al. 2005). Furthermore, Robins and Birkenholtz (2003) reported that 84% households in the US use fertilizers and 64% apply pesticides to their lawn. With estimates that urban land area covers roughly 3-5% of the US (Ludowski et al. 2005; Milesi et al. 2005; NRCS 2007), residential lawns come to represent a standard characteristic of urban developments by covering 20-30% of urbanized land area.

As lawn area increases, the amount of anthropogenic inputs to new lawns also increases in an environment where management occurs at an individual level that is largely unregulated (Robbins and Birkenholtz 2003). With a large majority of lawns actively being managed, land management could considerably influence soil functioning of lawn systems (Kaye et al. 2005). Surveys to determine how homeowners manage their lawns show that many homeowners did not have a clear understanding of the chemical composition of the fertilizers and pesticides they applied to their lawn and typically did not manage their lawn appropriately (incorrect amount and blend of fertilizer for turf species and wrong application time) (Osmond and Hardy 2004; Robbins et al. 2001).

With a steady contribution of inputs to lawns by homeowners, forethought is needed on how homeowner management and chemical input will influence the environment. Fertilizers contain nitrogen (N) and phosphorus (P) that can have direct impacts on water quality. Runoff from impervious surfaces transports fertilizer straight to stormwater inlets and excess nitrate (NO_3^-) and P loads that leach from the soil raise nutrient levels in streams impacting stream biota and causing eutrophication in lakes. Many general use pesticides have been found to negatively impact avian and aquatic species and the detrimental effects of lawn pesticides on fish and macroinvertebrate populations have caused some states to implement a maximum daily load criterion to control the chemical inputs to water resources (Robbins et al. 2001). Several key factors that affect nutrient loss from lawn soils also are important in homeowner management: amount and timing of application, quantity and time of watering, soil infiltration rate, species of turfgrass, fertilizer type, vegetation density, and years since turf establishment

(Easton and Petrovic 2004; Gold et al. 1990; Liu et al. 1997; Osmond and Hardy 2004; Petrovic 1990).

Aside from land management, the construction of residential developments play a role in determining the lawn and soil environment. The structure of soil can be greatly altered by development due to site clearance, introduction of new soil material, construction of impervious surfaces, reshaping of the land, and compaction from construction equipment. Previous investigators have found that soil processes and functions such as soil nutrient cycling (Law et al. 2004; Petrovic 1990) and water permeability (Bullock and Gregory 1991; Hamilton and Waddington 1999) are related to the age of the lawn or time since development. The disturbance from property construction has been related to a decrease in soil tilth in which surface soils may have increased compaction reducing soil structure and exposure of sub-surface soil layers can lead to nutrient and organic matter (OM) loss. These actions impact the fertility of the soil and its ability to maintain soil OM levels, biological diversity, and nutrient balance.

As a development and lawn matures the OM, total carbon (TC), and total nitrogen (TN) contents of a soil have been found to rapidly accumulate in the first 10-20 years after lawn establishment and then reach a steady-state around 40-50 years (Petrovic 1990; Qian and Follett 2002). This pattern has emerged in several studies 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 TC and TN 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).

The starting point of nutrients in developed soil will be influenced by prior land use; Qian and Follet (2002) identified soil organic C (SOC) on golf course fairways less than 10-years old had 24% lower SOC if they were previously agricultural land than fairways constructed on native grasslands. Both previous land use (agricultural or forestland) and construction practices used during development will determine the initial basis of soil OM and nutrient content but the lack of intense disturbance after development along with management inputs aid in this progression of OM accumulation and soil fertility.

Relationships with lawn age have also been tied to lawn management practices. Law et al. (2004) compared the amount of fertilizer applied to lawns in two urban watersheds in Baltimore County, Maryland and found the quantity of fertilizer correlated with the age of the development, soil bulk density, and the soil N content. The newer developments were found to apply more fertilizer likely to compensate for reduced nutrient levels during lawn establishment (Law et al. 2004).

Urban impacted areas have been identified as having distinct characteristics such as the urban heat island effect, acid rain from industrial pollution, and increased amounts of impervious surfaces (Groffman et al. 1995; Pouyat et al. 2002; Vitousek et al. 1997). Recent studies have found that urban environments have altered soil ecosystem processes in comparison with undeveloped, rural, or agricultural environments (Hope et al. 2005; Kaye et al. 2005; McDonnell et al. 1997; Pouyat and Turechek 2001). For example, Zhu and Carreiro (1999) found higher nitrification rates and NO_3^- concentrations in urban versus rural forest soils. Additionally, processes influencing organic C pools in forest stands along an urban to rural gradient were found to differ as a result of environmental

conditions. These urban impacted forest soils had high abundances of earthworms that redistributed soil horizons and fragmented litter, elevated soil temperatures that accelerated decomposition, and higher exposure to atmospheric pollutants such as ozone that reduced litter quality and decomposition (Carreiro et al. 1999; Pouyat et al. 2002). As a result urbanized systems generate a multitude of stressors that have a complex influence on the urban soil environment.

Although urban research is in the process of identifying direct and indirect effects urbanization has on nutrient cycling, the majority of urban research has been done in intensely developed areas with few published studies available on urban impacts in the Northeastern region and residential soil ecosystems. Similar to land use trends occurring across the US, the state of Vermont had increases in percentages of developed land (+31%) from 1982-1997 that were close to double the increase in population (+17%) during 1980-1997 (Census 2007; NRCS 2007). In comparison Chittenden County, VT, home to approximately one-fourth of Vermont's residents, reflected a greater impact from urbanization in which land development increased by 47% and population increased by 24% during these time periods (Census 2007; NRCS 2007). Urbanization has continued to expand in VT and has led to shifts in land use; developed land increased an additional 9% from 1997 to 2003 with a corresponding decrease to both percentages of agricultural (-7%) and forested (-9%) land (NRCS 2007). Due to these recent patterns of urbanization, Vermont provides an opportunity to study residential soils in an actively urbanizing landscape.

The goal of our research was to determine how residential development affects soil quality in Chittenden County, Vermont. Doran and Parkin (1994) define soil quality as “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.” We used a set of established soil measurements as soil quality indicators to identify baseline conditions of residential lawn soils and facilitate comparison among residential developments. The specific objectives of our study were to determine if important soil processes (potential nitrogen mineralization (PNM), potential net nitrification (PNN), and soil respiration) and properties (TC, TN, and microbial biomass carbon (MBC) and nitrogen (MBN)) of residential lawn soil ecosystems differed with increasing time since development, increasing development intensity, and lawn management practices.

2.2. Methods

2.2.1. Study Area

The study area is located in the Lake Champlain valley of northeastern Vermont, USA. Sites were selected from seven towns within Chittenden County including Burlington, Colchester, Essex Junction, Shelburne, South Burlington, Williston and Winooski (Figure 2.1). Chittenden County covers an area of 137,788 ha (340,480 ac) with a population of approximately 150,069 (Census 2007). Burlington (latitude 44.488 N, longitude -73.226 W), the largest city in Vermont, supports a population of just under 40,000 (BDPZ 2006; USDA/SCS 1974). The towns were chosen based on data

availability for the urban metrics of interest and because they include a gradient of urban intensity.

The physiographic region of the study area is characterized by the Champlain Lowland with rolling terrain that is bounded on the west by Lake Champlain and the east by the Green Mountains. The bedrock includes sedimentary limestone, sandstone and shale. The soils in Chittenden County and the Champlain Lowland are dominated by glacial till overlain with sediments accumulated during periods of glacial retreat where Lake Vermont covered much of the county and later the Champlain Sea that formed in areas of the valley with elevations less than 98 m (320 ft) above current sea level (Wright 2003). Soil types range from fine-textured soils that accumulated from quantities of lacustrine clay and silt corresponding to the glacial lake-bottom, coarse-sandy soils where deltas formed along the Winooski and Lamoille River as they drained into the Champlain Sea, and glacial till deposits located in higher elevations on the eastern edge of the county (Meeks 1986; USDA/SCS 1974).

The elevation of the valley, in the western part of the county, is less than 152 m (500 ft) with Burlington's elevation ranging from 31-101 m (100-330 ft). While the Green Mountains in the eastern edge of the county have elevations between 610-1219 m (2-4,000ft) (USDA/SCS 1974). The climate can be characterized by moderately temperate summers and cold winters (USDA/SCS 1974). For the Burlington area the mean annual precipitation for the period of 2000-2006 was 94.5 cm (37.2 in) with a mean monthly precipitation of 9.6 cm (3.79 in) and mean air temperature of 17.6°C (63.8°F)

during August and September of 2006, the months sampling was conducted (NDCD 2006).

2.2.2. Sampling Design

Residential households were stratified for site selection based on age of development (individual house age) and intensity of development in neighborhood. These variables were used to quantify impacts from urbanization activities on the residential landscape. The age of the home represents the year a parcel was developed and acts as a surrogate for years since lawn establishment. This variable of lawn age was used to capture potential changes in soil condition (nutrient levels and soil structure) that may occur after the initial disturbance from development, as identified in previous studies (Law et al. 2004; Scharenbroch et al. 2005; Qian and Follett 2002). Urban intensity was determined by the population density of Chittenden County. The intensity metric was used to portray levels of anthropogenic influence on the lawn from the surrounding environment. For example, higher densities of urbanization relate to higher road densities and automobile use (Pouyat et al. 1995) which elevates the impact of atmospheric contaminants to the lawn. Soil texture was included with the urban metrics for site selection as it can be an indicator of the soil nutrient capacity wherein fine-textured clay soils, with higher surface area and negative charge, have a higher potential for OM and C accumulation compared to coarse-textured sandy soil. Soil texture will therefore aid in controlling soil variability present as a factor of the soil texture classification. Methods for deriving the site selection variables are described next.

Lawn Age – This metric represents years since lawn establishment with the general assumption that minimal disturbance occurred to the lawn after it was established. Homeowner knowledge regarding areas of the lawn that may have been subject to recent impacts was considered prior to soil sampling. The year a house was developed was acquired from public records for the individual towns and geocoded by address with ArcGIS into a searchable data layer. For site selection lawns were classified into three categories based on age: less than 20 years old (1986-2006), 20-50 years old (1936-1985), or greater than 50 years old (pre-1935). Lawn age was used as a continuous variable (individual year house built) for statistical analyses.

Urban Density – The dataset PRIZM (Potential Rating Index by ZIP Markets; Claritas 2003) was used to extract levels of urbanization intensity in Chittenden County for site selection. This dataset defines household density at the resolution of US Census Block Groups with three intensities identified as High, Medium, or Low in which density becomes lower with increasing distance away from Burlington center (Figure 2.2.). Further analyses used two urban density functions as continuous variables to better represent the development intensity around sampled sites. The first variable, population density, was an estimate of the 2003 population per square mile in Chittenden County per census block group (Claritas 2003). This variable has coarser resolution as census block groups vary in size throughout the county and can cover large heterogeneous tracks of land. The second variable, average parcel size (APS), represents the average size of parcels (acres) within a one-quarter mile radius of the sampled site. Other radius widths that ranged up to 1 mile were tested by visual interpretation and comparison of

coefficient of variation values. However, one-quarter mile was determined the appropriate radius that captured the development type of the area surrounding the site and neighborhood. APS provides a finer scale of measurement for development intensity at each site.

Soil Type – To represent contrasting characteristics of coarse and fine textured soils, soil hydrologic groups were used to filter soil series to a generalized classification of soil texture as defined by the 1974 Chittenden County soil survey (USDA/SCS 1974). Sites were selected from hydro groups A (high infiltration rate and low runoff potential with a moderately coarse to sandy texture) and D (very low infiltration rate and high runoff potential with a moderately fine to fine texture) (USDA/NRCS 2005). A limited number of group C soils were sampled to represent the fine textured class in a few lawn age-density categories in which group D soils were poorly represented or absent.

In urban areas it is common practice for fill to be brought in to new developments (Schleuß et al. 1998). However, as no data were available from public records to detail the actuality of burial or mixing of soil with fill material during development of selected properties, the soil survey was used to provide an approximation of soil type. Consequently, the soil types represented by the classification used to identify sampling sites could be different from those actually sampled in the field. In this study, the soil survey was only used to guide sampling; analyses of field samples (described below) were used to generate quantitative characteristics of soils for statistical analysis.

The categorical variables were linked at the parcel level in ArcGIS to create a pooled dataset for site selection over the seven towns. Thirty households were randomly selected from each lawn age-urban intensity-soil type category (see Appendix D). These selected households were sent a mailing with information regarding the study and a study involvement form with a pre-addressed envelope that willing participants could return. From the returned mailings, a minimum of three residential lawns per category were selected for soil sampling.

2.2.3. Data Collection

A total of 65 lawns were sampled in late summer, early fall (August and September) of 2006 (Table 2.1). As measurements of microbial biomass and soil N dynamics can be sensitive to seasonal variation these indicators were used to capture a snapshot characterization of the lawn and soil condition for comparative purposes and were not meant to be generalized over a broader timeframe than the months sampled. Soil cores were sampled from the dominant lawn vegetation during a single site visit. Three to four soil cores were extracted from each lawn to account for inter-lawn variability such as sunny versus shady patches and fill from development, while minimizing the impact to the homeowner's lawn from sampling. The top 10 cm of the soil were sampled using a soil bulb corer (Bulb Hound Garden Planter by Hound Dog) and the thatch (turf plus root mass) was cut from the soil core and returned to the lawn. The intact soil cores (5.7 cm diameter to a depth of 6-10 cm) were transported from the field in plastic bags placed in a cooler. Soils were sieved the day of sampling through a 10 mm and 5 mm sieve to remove large roots and vegetation while minimizing the

impact to the soil for biological measurements. The soil cores were then homogenized into a composite sample and split into two sub-samples for analysis. One sub-sample was sent to the University of Vermont's Agricultural and Environmental Testing Lab (UVM-AETL) for background soil tests and the second sub-sample was held at field moist conditions and stored at 2.78°C (37°F) up to 2 days until processed for microbial biomass analysis, potential mineralization, potential nitrification, and respiration. The specific methods for these tests are described in detail in the next sections. In addition, a lawn care questionnaire was administered to homeowners of the sites sampled to identify the extent to which the site was actively managed.

2.2.4. Analytical Samples – Soil Properties

Bulk density was estimated from the soil cores collected for chemical and physical analysis. The estimated bulk density (g cm^{-3}) was calculated as the total dry mass of the cores used to create the composite sample divided by the total core volume. Total dry mass of the composited cores was calculated as the total fresh mass of the individual cores multiplied by the gravimetric soil moisture content of a soil aliquot. This dry to fresh weight ratio (g/g) was determined by weighing ~5 grams of fresh composite soil before and after drying at 104°C for 24 hours. Total core volume was based on the summed depths of the holes and cross-sectional area of the corer from which the individual soil cores were taken. Measurements were recorded in 0.01 cm increments and the depth measurement was adjusted for the depth of thatch removed (~1.3 cm).

The sub-sample of soil sent to the UVM-AETL was used to measure a suite of soil properties. Soil TC and TN content were measured by combustion on a CN Element

Analyzer and weight loss on ignition estimated percent OM (Schulte 1995). Salt pH (pH_s) was measured with a pH electrode in 0.01 M calcium chloride solution and water pH (pH_w) calculated as $pH_s + 0.6$ (Eckert and Simms 1995). Extractable elements: P, aluminum (Al), macronutrients (magnesium (Mg), potassium (K), and calcium (Ca)), and micronutrients (iron (Fe), manganese (Mn), copper (Cu), boron (B), sodium (Na)) were extracted using a Modified Morgan extraction (ammonium acetate solution at pH 4.8) (Wolf and Beegle 1995). Extractable or available P was analyzed colorimetrically and the remaining elements were analyzed on an ICP-AED. The effective cation exchange capacity (CEC) was calculated as the sum of extracted cations (Ca, K, Mg) (Ross 1995). A soil texture analysis was performed using the hydrometer method (Gee and Or 2002) to determine percent sand, silt, and clay for each site to verify the site's soil texture against the Chittenden County soil survey.

2.2.5. Analytical Samples – Soil Processes

The second sub-sample of soil was used to determine MBC and MBN and inorganic C and N using the chloroform fumigation and incubation (CFI) method adapted from Jenkinson and Powlson (1976) and Paul et al. (1999). For microbial biomass content soil was fumigated by weighing 20 g of field moist soil into 50 mL beakers that were subsequently placed into a desiccator containing 10 mL of chloroform and lined with moist paper towels (contained in a fume hood). After bringing the chloroform to a boil using a vacuum pump the desiccator was closed and the soil was kept in contact with the chloroform for 16-24 hours. After the fumigation the soil was placed into a quart mason jar and inoculated with a small amount of fresh soil (0.2 g soil) and incubated for

10 days at room temperature (20-22°C) in the dark. The chloroform fumigation kills and lyses living microbial cells in soil. This method assumes that the resulting measurements of carbon dioxide (CO₂) evolution and ammonium (NH₄⁺) plus NO₃⁻ accumulation in soil during the incubation is due to the activity of new microbes (introduced with the soil inoculum) that grow on the organic C and N lysed from the original microbial biomass.

Microbial biomass C was measured from the fumigated samples at the end of the 10 day incubation by sampling the CO₂ concentration in the headspace of the mason jar. The gas was sampled by syringe through a rubber septa placed in the lid of the jars and gas samples were stored in 10 mL glass crimp-top vials until analysis on a gas chromatograph (Shimadzu GC-17A, ECD sensor) optimized for the analysis of greenhouse gases including CO₂ (Appendix B). The syringe was flushed with room air between samples to avoid between sample contaminations. Microbial biomass C was calculated by dividing the flush of CO₂-C by the proportionality constant (k_c) 0.41 suggested by Vorney and Paul (1984), without subtractions of a control or unfumigated incubation as it may better represent the active soil C pools (Franzluebbers et al. 1999). The microbial biomass C concentration of CO₂ was converted into CO₂-C per dry weight of soil expressed as $\mu\text{g C g}^{-1}$ dry soil.

Microbial biomass N was measured at the end of the 10 day incubation on the fumigated soils by extraction using a 2 M potassium chloride (KCl) solution (Paul et al. 1999). After microbial C sampling 80 mL of KCl solution was added to the mason jars containing 20.2 g of soil and the soil:KCl slurry was placed on a shaker table for 1 hour and then left to settle before being filtered. The filtrate was stored in 50 mL

polypropylene centrifuge tubes at -30°C (-22°F) until colorimetric analysis (Lachat QuikChem AE). Microbial N was calculated as the total inorganic N flush (NH_4^+ + NO_3^-) from the fumigated 10 day incubation and was expressed as $\mu\text{g N g}^{-1}$ dry soil. A proportionality constant was not applied (Groffman and Crawford 2003; Groffman et al. 2006).

Along with the fumigated incubation a concurrent incubation was run on un-fumigated soil to measure inorganic N and CO_2 production using an equivalent amount of fresh soil (20.2 g) and conditions as that of the fumigated samples. At the end of the 10 day un-fumigated incubation, soil respiration was measured following methods described above for microbial $\text{CO}_2\text{-C}$. Soil respiration was calculated by dividing the flush of $\text{CO}_2\text{-C}$ by the incubation time (days) for an estimated amount of CO_2 evolved per day and was expressed as $\mu\text{g C g}^{-1}$ dry soil day^{-1} .

Potential net nitrification and N mineralization were measured using KCl extractions. To obtain the starting condition of the soil, an initial extraction was done on 7.5 g of fresh, un-fumigated soil with 30 mL of 2M KCl solution when the incubations were set up. A final extraction was completed at the end of the 10 day incubation on the un-fumigated soils using the same procedures as the microbial N extraction. Potential net N mineralization and PNN were calculated as the difference in accumulation of NH_4^+ plus NO_3^- and NO_3^- respectively from extractions on the 10 day un-fumigated incubation from the initial extraction on fresh soil divided by the incubation time (days). Ammonium and $\text{NO}_3\text{-N}$ were measured as described above for MBN and expressed as $\mu\text{g N g}^{-1}$ dry soil day^{-1} .

2.2.6. Homeowner Lawn Care Survey

Lawn management practices on the sampled lawns were assessed from a homeowner survey. Information collected on the survey included: estimated fertilizer use and amount in the past 12 months, timing of fertilizer application(s), mowing and water use practices. This survey was adapted from the lawn management survey used by Law et al. (2004) with permission from the author (see Appendix A). The survey captured the current lawn management practices (past 12 months) and as a result 'fertilizer use' in statistical analysis represents whether the lawn is currently fertilized (Y) or currently non-fertilized (N). Supplemental property information was also gathered from homeowners prior to sampling to identify *a priori* areas of the property that should not be sampled such as septic fields, areas of pet usage, as well as soil recently disturbed due to city services or homeowner activity.

2.2.7. Statistical Analysis

Sixty-five lawns were sampled however four sites were excluded from data analysis as they were uncharacteristic of the other households sampled or were missing survey data. Of the removed sites, one was excluded due to the homeowner's lack of knowledge on placement of the septic system leach field and soil test results indicated the potential of contaminated samples. Two sites were removed as their lawn management was controlled by associations and differed from the remaining sites that represented management decisions of individual homeowners. Furthermore of the 61 remaining sites, one value was removed from each of the N mineralization processes (PNM and PNN; n=60) due to potential contamination during sample processing.

The relationships among the soil quality indicators, urban metrics (lawn age, urban intensity, current fertilizer use) and existing soil properties were examined using correlation analyses and t-tests. Linear regression analyses were used to identify whether urban variables influenced the soil quality processes. Normality testing with Shapiro-Wilk and Kolmogorov-Smirnov identified the soil quality variables were normally distributed and independent. Lawn age, population density, and APS were \log_{10} transformed to account for positively skewed distributions.

A Student's t-test identified if there were significant differences among the soil quality indicators in relation to soil type (hydro groups) and land management (current fertilizer use). The Pooled t-test method was used, except for variables where outliers created unequal variances in which case the Satterthwaite method was applied. However comparable p-values were produced regardless of the equality of variance assumption and method. Pearson Correlation analysis identified significant relationships (p-value ≤ 0.05) among soil biological, physical, and chemical properties and the urban metrics. Multivariate linear regressions were performed to investigate the correlations of the soil quality indicators (MBC, MBN, soil respiration, PNM, and PNN) to lawn age, urban intensity, lawn management practices and the 18 soil properties (significant at the 95% confidence level). To reduce the dimensionality of the soil property dataset a Principal Component Analysis (PCA) using a varimax rotation was used on the 18 soil properties analyzed by the UVM-AETL lab. Total C and TN were included in PCA as they were correlated to microbial biomass measures and the soil texture variable '%Silt+%Clay' was used in the PCA as the percentages of sand, silt and clay are autocorrelated.

Principal components (PC) that had eigenvalues greater than 1, a high proportion of explained variance and represented an interpretable relationship were considered significant. Each significant component consists of a linear combination of weighting factors or eigenvectors for each of the 18 soil properties that depict the relative contribution of that variable to the component. Multivariate linear regressions were performed on the five soil quality indicators with 6 independent variables, 3 urban metrics and 3 soil property PCs, and one model per indicator for each urban intensity variable was generated (Table 2.2). Tolerance and Variance Inflation Factors (VIF) were used to test for multicollinearity of the independent variables; no collinearity was detected as tolerance values were greater than 0.6 and VIF values were less than 2.0. The highest and lowest values for MBC were removed for regression analysis (n=59) and MBN had 1 observation removed for normality of the residuals (n=60); all of the removed points had studentized residuals greater than three standard deviations from mean. SAS (v8) statistical software was used for all analyses. Unless noted, reported values are presented as a mean with standard error in parentheses.

2.3. Results

2.3.1. Physical and Chemical characteristics of lawns

Soils for all lawns sampled in this study ranged from sandy to loam texture (Table 2.3) with the majority of the sites having sandy-loam and loamy-sand soils or soil hydro group A. No hydro group D soils were observed. In general, the soil properties in the lawn soil had low percent coefficient of variation (CV) values with the lowest CV

observed for TC and TN content and the highest CV with available P and the metals Al, Cu, Zn, and Fe (Table 2.4). Calcium was the most abundant cation in the lawns and K was the cation with the lowest coefficient of variation. Taken as a whole the C:N ratio and percent OM in the lawn soil had a mean of 14.7 (0.2) and 3.3 (0.1) respectively and a mean pH_w of 6.1 (0.07).

2.3.2. Relationships among soil and urban variables

A correlation analysis demonstrated that several soil quality measures were correlated with the texture components (Table 2.5). Percent sand had a negative correlation with several dependent variables including MBC, MBN, and TN content with percent clay having a positive relationship. The results of the particle size analysis verified that the original soil hydro groups did not correspond to the developed soil classification but soil texture had a significant influence on the soil quality indicators and was used in further analysis. Two-sample t-tests further determined that soil quality measures differed between the coarse-textured soil hydro groups A and B. The C:N ratio was significantly higher ($p\text{-value} \leq 0.05$) in hydro group A soils with MBC, MBN, and TN significantly higher in hydro group B soils.

Relationships were also found between the soil properties, soil processes and urbanization variables (Table 2.6). Microbial biomass C and MBN had a significant positive correlation with soil TC and TN content. Microbial biomass N was found to be significantly correlated with soil CEC and cations (Ca, Mg, and K). Percent OM was highly correlated ($p\text{-value} \leq 0.001$) with MBC and MBN with a significant correlation at $p\text{-value} \leq 0.05$ with respiration. The TC and TN content had significant positive

correlations to Log₁₀ Lawn Age (Figure 2.3, Table 2.6). In addition, MBC and MBN also had positive correlations with Log₁₀ Lawn Age however rates of respiration, PNM, and PNN were not correlated with Log₁₀ Lawn Age (Figure 2.3). The urban density variables, Log₁₀ Population Density and Log₁₀ APS, did not significantly explain variability in the majority of soil quality variables (Figure 2.4, Figure 2.5). A significant negative correlation was identified between PNN and Log₁₀ APS in which as the surrounding lot size increased or became less dense it negatively influenced PNN.

Two-sample t-tests identified that lawn management (fertilization) had an influence on three of the soil quality indicators. Respiration and TC were significantly higher on the currently non-fertilized lawns (p-values 0.01 and <0.01 respectively) with PNM significantly higher on currently fertilized lawns (p-value 0.02). Available P and K, typical components of fertilizer, were not significantly related to fertilization (p-values 0.15 and 0.09 respectively) in which currently non-fertilized lawns had similar mean P concentrations of 10.6 mg kg⁻¹ (2.0) to currently fertilized lawns at 8.7 mg kg⁻¹ (1.5).

The first three principal components accounted for 61% of the variation in the physical and chemical soil attributes (Table 2.7). The first principal component (PC1) explained 37% of the variance and related to indicators of the exchange capacity of soil. Positive loadings of PC1 correspond to high concentrations of base cations (Ca, Mg, K), high CEC, high measures of pH, and high concentrations of micro-nutrients (B, S). Negative loadings of extractable Al were also associated with PC1. The second principal component (PC2) represented the OM composition of soil and explained an additional 16% of the variance. PC2 corresponded to high positive loadings of percent OM, TC and

TN content. The third principal component (PC3) explained 9% of the variation and corresponded to high concentrations of available P and Zn and negative loadings of percent silt plus clay. This relationship is explained by significant correlations of extractable P and Zn with soil texture. Extractable P and Zn had a positive relationship with percent sand and P was negatively correlated to percent clay. As the majority of the soil is coarse-textured this relationship may be indicative of increased management inputs (higher P) applied to sandier soils. These three principal components were utilized in the multivariate regression analysis described next.

2.3.3. Multivariate Analysis – Population Density

Multiple linear regressions for the mineralizable C and N processes (MBC-PD, MBN-PD, Respiration-PD, PNM-PD, and PNN-PD) to lawn age, population density, land management, and soil property PCs were found to explain up to 48% of the variation in the dependent variables (Table 2.8). The regressions MBN-PD and MBC-PD yielded models that explained the most variation in the data with adjusted R^2 values of 0.48 and 0.43 respectively. There were three significant predictors in the MBN-PD model: PC1, PC2 and Log_{10} Population Density. The significant variables in the MBC-PD model were Log_{10} Lawn Age, Log_{10} Population Density, PC1, and PC2. The models produced for Respiration-PD, PNM-PD and PNN-PD each explained $\leq 15\%$ of the variation. Whether the lawn was currently fertilized was the only significant variable in the soil respiration model. The PNM model was significantly predicted by fertilization, PC1 and PC2 while PNN was significantly predicted by PC1.

2.3.4. Multivariate Analysis – Average Parcel Size (APS)

Multiple linear regressions for the five soil quality processes were also explored using the APS variable (Table 2.9). Again regressions for MBN-APS and MBC-APS yielded models that explained the most variation but the percent of explained variance decreased to 47% and 32% respectively from the models MBN-APS and MBC-APS. Model MBN-APS was predicted by PC1, PC2 and PC3 though none of the urban metrics were significant in the model. Similarly the MBC-APS model had PC1 and PC2 as significant predictors and the model did not include significant urban metrics. The Respiration-APS model was identical to Respiration-PD with a significant influence by current fertilization. The model PNM-APS explained 15% of the variation and utilized model variables and coefficient values identical to that of PNM-APS. The PNN-APS had a significant negative correlation to Log_{10} APS.

2.3.5. Homeowner Survey

The homeowner land management survey (n=64) identified that 13% of all homeowners had prior soil testing of their lawn and that 53% of all homes sampled currently applied fertilizer to their lawns. Of that 53% that currently fertilized, 56% of homeowners self-applied fertilizer to their lawns and 44% employed a professional service. Most homeowners returned grass clippings to the lawn when mowing (73%) with a smaller percent bagging and removing the clippings completely (11%). In addition, 88% of the homeowners used water for one or more of the following outdoor activities: wash car, water garden, lawn or landscaping, clean sidewalk or driveway, and

recreational use. Thirty-one percent of homeowners reported to watering their lawns in 2006.

Based on the lawn nutrient recommendations provided by UVM-AETL, the soil test results showed that 71% of the lawns that were currently fertilized (n=31) were categorized with optimum levels of P in their soil and 10% of the lawns had excessive amounts of P. These results were similar for soils regardless of lawn care service or homeowner applied fertilizer applications. However 32% of the currently non-fertilized lawns (n=28) had excessive amounts of P and 29% had optimum levels of P.

2.4. Discussion

2.4.1. General Lawn Characteristics

The soil pH_w for all lawns in the study were consistent with those reported as a healthy pH range for turfgrass growth of slightly acidic to neutral soils (pH 6-7; UMass Ext 2004) and consistent with data reported by Sharenbroch et al. (2005) for pH ranges of sampled urban landscapes. The pH of lawns have been shown to be distinct from other urban land use classes which is thought to be due to factors associated with lawn management (Pouyat et al. 2007).

Guidelines for turfgrass from UMass Ext (2004) report soil CEC values of 10-15 and proportions of basic cations (percent base saturation) as 70% Ca, 12% Mg, and 4% K for sufficient nutrient conditions and availability to support turf growth in New England. The base saturations for our sampled lawns have proportions of Ca and Mg that meet the adequate levels (70.0% and 12.6% respectively) however our observed mean K and CEC

values fall below these guidelines (2.0% and 7.3 respectively). In addition the range of percent OM in our lawns was 1.5-5.0% with a mean of 3.3 which is lower than recommended 7-10% OM for turf soils (UMass Ext 2004). Given that half of the sampled soils had a sandy texture (sandy loam), and on average were slightly acidic with low OM this may account for the lower CEC and percent base saturation of K, as these factors influence nutrient levels, water holding capacity, and structure of soils.

The mean values obtained for the soil quality processes (MBC, MBN, soil respiration, PNM, PNN; Table 2.4) fall within the same order of magnitude of values reported in other urban studies. In relation to urban riparian zones (forested and herbaceous vegetation) MBC and soil respiration were found to be slightly higher (mean values 663 mg C kg^{-1} and $20.1 \text{ mg C kg}^{-1} \text{ d}^{-1}$ respectively) and the PNM and PNN lower (0.35 and $0.15 \text{ mg N kg}^{-1} \text{ d}^{-1}$ respectively) than our reported mean for all lawns (Groffman and Crawford 2003). However the MBN given for urbanized plots of 45 mg N kg^{-1} from their study using CFI was similar to our reported mean value. Using twenty day incubations Scharenbroch et al. (2005) reported soil respiration values of younger and older lawns that ranged from 14.8 - $19.6 \text{ } \mu\text{g C g}^{-1} \text{ d}^{-1}$ which fall within the respiration range from this study of 2.0 - $26.6 \text{ } \mu\text{g C g}^{-1} \text{ d}^{-1}$ across all lawns and ages. Overall the values produced by the soil quality indicators in this study compare well to those reported from urban soils in other studies.

2.4.1. Lawn Age

As was expected lawn age had a significant positive correlation with TC and TN content in the soil. In addition, lawn age had a significant influence in the MBC-PD

model. Since lawn age represents the length of time since the disturbance of development, it therefore relates to the soil's post-development maturation. Initially after development the soil may be compacted and have reduced soil structure lessening the soil fertility (Law et al. 2004; Scharenbroch et al. 2005). Over time as the OM builds up and aggregates form in the soil; nutrient contents increase (TC and TN) and the bulk density of the soil decreases making the soil more nutrient rich and productive (increased microbial activity). However, lawn age did not demonstrate a relationship with MBN, soil respiration or potential N measures after adjusting for other variables in the model. We had expected an influence of lawn age on MBN as they were significantly correlated (p -value <0.01). This relationship may have been accounted for with the inclusion of PC2 in the models, as Log_{10} Lawn Age had a significant correlation ($p <0.001$) with PC2, the organic matter component (Figure 2.6).

Due to this progression in the soil we had expected to find an increase in soil respiration, PNM and PNN over time. Scharenbroch et al. (2005) reported finding younger residential lawns (<10 years) had decreased measures of MBN and PNM compared to lawns greater than 50 years old. One reason we may not have seen this pattern could have been due to more recent disturbances in some of the older lawns. We assumed that the lawn had not experienced major disturbance since lawn establishment and designed the composite soil sampling to try and minimize the effect of intra-lawn variability and disturbance history. However, due to homeowner turnover this assumption could not always be verified by homeowners.

The present study is consistent with others (Golubiewski 2006; Law et al. 2004; Scharenbroch et al. 2005) in finding significant relationships between soil properties and processes to the years since lawn establishment, likely representing the last major disturbance to the soil. However, the length of time necessary for soil to bounce back from smaller disturbances such as soil excavation for utilities, re-landscaping, and automobile use on lawns may need to be considered as these factors directly impact the lawn surface and may influence soil conditions. In addition, the build-up of OM could also differ depending on whether the lawn was developed on previously agricultural or forest land (Qian and Follett 2002) and factors of development that gauge the construction disturbance (whether fill was mixed or buried existing soil).

2.4.2. Density metrics

As we expected, MBC and MBN were negatively impacted by increased urban intensity in which MBC-PD and MBN-PD decreased as population density increased. However, we did not see a similar response with soil respiration. Increased urban influences in dense residential areas such as higher road density and smaller parcel sizes may lead to increased contaminants from fossil-fuel combustion (Beyer et al. 1995; Lorenz and Kandeler 2006) and compaction from human disturbance to the lawn (Kurfis and Bierman 2002) that negatively impact the lawn's microbial activity. Beyer et al. (1995) hypothesized that oil and gasoline from increased auto use in urban areas may cause soil microorganisms to specialize in the use of hydrophobic carbon in the organic layer.

Carreiro et al. (1999) reported that decomposition rates and microbial biomass were greater in rural forest stands than in urban forest stands. However no significant differences in microbial activity were found in comparisons of soils from urban to rural riparian zones (Groffman and Crawford 2003). The response of microbial biomass to urban density can largely be driven by changes occurring in the SOC. Groffman et al. (1995) found reductions in the labile and readily mineralizable SOC pools in urban forests and increased storage of C in recalcitrant pools compared to rural forest stands. Readily mineralizable and labile pools of SOC are thought to be impacted by altered environments in urban areas caused by factors such as urban heat island effect, land management, non-native earthworm activity, N deposition, and reduced litter quality (Carreiro et al. 1999; Groffman et al. 1995; Neff et al. 2002). Increased temperatures, fertilizer inputs and activities of earthworms tend to speed up the decomposition of available C while other factors effectively reduce the availability of nutrients to organisms.

As the surrounding lot sizes increased (became less urban and less dense) PNN decreased in the PNN-APS model. We had expected to see both PNN and PNM decrease due to the hypothesis of lower microbial biomass in dense areas thereby reducing these microbial mediated processes. However, PNM did not correlate to either density metric. Responses that have been reported in the literature of N processes along urban density gradients as well as urban to rural comparisons have been quite varied. Baxter et al. (2002) and Zhu and Carreiro (1999) reported that NO_3^- concentrations and PNN were significantly higher in urban forest stands than in rural forests, but that NH_4^+

concentrations and PNM were not significantly different. However, Zhu and Carreiro (2004) found urban forest stands had increased mineralization rates compared to rural stands.

Metrics of urban density patterns were successful in representing ecological trends in a study done by Pouyat et al. (1995) in which factors relating automobile use (road density and traffic volume) were the strongest predictors in characterizing soil chemical properties along an urbanized gradient. Both density predictors tested in our study produced models that explained similar amounts of variance in the soil quality variables (Table 2.8; Table 2.9). Three regression models included urban intensity as a significant predictor. However these final models did not differ largely in the amount of explained variance from models where density was not significant for the dependent variables. Both urban intensity predictors were not found to have a collinear relationship with other independent variables but they were found to have a weak correlation with PC3. Overall the results suggest that the density of homes or people were not driving functions after adjusting for the other variables. Density may not have a straight forward role as it may be representing influences of environment conditions (e.g. urban heat island), exposure to anthropogenic activities (e.g. atmospheric pollutants), legacy of previous land use (e.g. conversion from agricultural land), or it may not be right predictor to capture the influence of development patterns in less developed areas like Chittenden County, VT.

2.4.3. Lawn Management

As was expected fertilizer use was a significant predictor for PNM and fertilized lawns had significantly higher rates of PNM in the soil. Fertilization was not influential in the PNN models but was nearly significant with p-values of ≤ 0.1 . Zeglin et al. (2007) found increases in the concentrations of extractable $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in two grassland ecosystems with ammonium nitrate N additions compared to an unfertilized grassland control. As fertilization adds a ready source of mineralized N to the soil system, it is not surprising to find significant relationships between fertilizer use and measures of N mineralization. Hope et al. (2005) found $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentrations were significantly predicted by urban variables (population density, percent impervious cover) and socioeconomic factors (income per capita) in an urbanized arid soil environment but noted that these variables likely account for a strong influence of local anthropogenic activities (fertilization, irrigation).

Our findings of significantly lower OM and TC on currently fertilized lawns suggest that fertilizer application stimulated increased microbial oxidation of organic C sources, accelerating the breakdown of soil OM compared to currently unfertilized lawns. This relationship can also indicate that fertilized turf is allocating fewer resources belowground, as fertilization is providing a readily available nutrient source (less need of roots), reducing fine roots and root exudates that would increase soil C pools (Bowden et al. 2004). A decline in SOC on plots fertilized with an NPK source was also found in long-term studies on organic C concentrations in agricultural fields (Khan et al. 2007). In addition, Neff et al. (2002) found that N additions had the potential to increase the

decomposition of labile soil OM but stabilized the recalcitrant pools of OM. On the other hand, fertilization has been reported to increase the organic compounds in the soil (Golubiewski 2006; Malhi et al. 1997). Fertilization can be beneficial in improving soil characteristics such as maintaining and increasing the above- and below-ground plant biomass which in turn provides the return of OM to the soil with plant senescence and root decay (Pouyat et al. 2002; Qian and Follett 2002). This recycling of biomass in the soil provides labile C that can improve aggregation, infiltration, microbial activity, and decrease bulk density (Bronick and Lal 2005; Haynes and Naudi 1998). Haynes and Naudi (1998) cited a study where long-term application of superphosphate on a pasture rapidly accumulated OM over the first 10 years of the study and then stabilized at a level 15% higher than the unfertilized pasture.

In our study fertilization did not have a significant relationship with microbial biomass. Ajwa et al. (1999) also reported a non-significant relationship of long-term fertilizations in Konza tallgrass prairie and microbial biomass measurements. Our data did show that soil respiration was significantly lower on currently fertilized lawns. Lower respiration was also reported from a short-term laboratory study where the addition of N caused a small non-significant decrease in microbial respiration rates of surface soils relative to the control (Fierer et al. 2003). Long-term research on the impact of fertilization in forest soils revealed increased soil respiration during the initial years following fertilization was likely attributed to increased plant productivity stimulating microbial activity (Bowden et al. 2004). Bowden et al. (2004) found the reverse trend after 13 years of fertilization in which soil respiration on fertilized plots was lower than

unfertilized plots thought to be caused by fertilized forests allocating less C belowground for root production, reduced soil C from root exudates and root turnover, and in turn impacted microbial populations.

As urban lawns receive management inputs (fertilizer and irrigation), lack major soil disturbance events, and have a prolonged growing season from warmer temperatures in urban areas, lawns have been found to have higher C densities and organic C than other urban and non-urban land use types such as agricultural lands and natural grasslands (Kaye et al. 2005; Pouyat et al. 2003; Pouyat et al. 2006). Differences in C densities of turf have been further differentiated based on management intensity in which turf in an urban land use that was highly maintained (recreational use) had higher C densities than turfgrass that was minimally maintained (urban park) (Pouyat et al. 2003). The potential for urban lawns to sequester C has positive connotations for the expansion of urban areas and how urbanization may impact land use conversion from forestlands to developed areas. However, the long-term influence of nutrient additions on lawns in relation to soil OM pools, respiration rates, and microbial activity are unclear (Bowden et al. 2004; Fierer et al. 2003; Haynes and Naudi 1998; Zeglin et al. 2007). Relationships between the short and long-term responses of soil processes and land management with fertilization and irrigation on turfgrass need further exploration to identify if a monoculture of lawns can increase C storage in urban soils.

In addition to N, P and K are both important components of commercial fertilizers however; extractable P and K did not have a significant relationship with current fertilization practices. A factor that may confound the significance of P could be

year to year differences in homeowner lawn management where the high levels of P on non-fertilized lawns may be due to earlier fertilization practices (Foster et al. 2003). In the lawn care survey the homeowners were asked about their current fertilizer use, characterizing the past 12 months, and a few homeowners that had not applied fertilizer in the past 12 months had applied it in previous years. In addition, newer homeowners that had lived in their residence for less than two years were unsure of previous lawn management. As P was variable among all lawns with a high percent CV, a legacy effect of P in soil may account for similar P concentrations among the currently fertilized and non-fertilized lawns (Bennett 2003; Foster et al. 2003). Bennett (2003) was not able to distinguish differences in four land use classes along a fertilization and urban density gradient using P concentrations and concluded that the previous land use history of agriculture may have obscured more recent influences of development. But the author did find available P concentrations in urban land use classes were lower than the surrounding agricultural land. Year to year variation in lawn management decisions as well as prior land use may confound the relationships between soil indices and management as the retention of nutrients in the soil system such as available P and pools of organic compounds such as OM may be altered by past management regimes.

2.5. Summary and Conclusions

This study provides further evidence that urbanization and land development impact soil properties and processes and that developed areas consist of a set of characteristics that can be used to distinguish residential lawns from one another. Urban

ecosystems have been identified with creating distinctive and multifaceted influences on soil ecosystem processes including increased air temperatures, introductions of non-native flora and fauna, altered atmospheric chemistry, and modifications of the hydrologic cycle (Carreiro et al. 1999; Groffman et al. 1995; Groffman and Crawford 2003; Pouyat et al. 2003). Although we found urban intensity significantly influenced microbial biomass and PNN, it did not play a large role in explaining variance in the soil quality indicators. As development density captures multiple characteristics of the residential urban area, the density impact on lawn systems may be obscured with correlated factors. Controlled experiments to explore and corroborate the effects of individual relationships and mechanisms such as the response of microbial biomass to soil compaction, elevated fossil fuel use, or differences in management practices can help to isolate key impacts of development density.

Similar to previous research, our study identified a positive correlation with the age of the lawn to organic components of soil such as OM, TC, TN and biological microbial biomass across a broad sampling of sites. This relationship can be a useful indicator for lawn management and inputs; recently established residential lawns will benefit from nutrient amendments but reductions in infiltration and soil structure from construction can negatively impact on water quality depending on lawn treatments. These relationships can be further elucidated by identifying if fluctuations occur from minor disturbances to lawns from routine anthropogenic activity and quantifying the differences in accumulation from land use history on residential soils.

Fertilization and irrigation on lawns can produce healthy, productive lawns. However if fertilization of lawns results in reduced OM and TC in soil and lower soil respiration as found in our study, than the long-term effects of homeowner lawn management may have implications on the potential for residential soils to sequester C and microbial mediated nutrient transformations that degrade soil contaminants.

Lawns are ultimately distinguished from other land uses by a combination of human activities including past and present land use as well as the current arrangement of the landscape with respect to roads and industrial influences (Qian and Follett 2002; Pouyat et al. 2007). Through this study we can conclude that residential areas in Chittenden County, VT differ in soil quality with homeowner lawn management practices and temporal trends from development patterns. The identification of these individual factors of residential lawns can be used to characterize residential neighborhoods and identify how development (single age versus multi-age neighborhoods) and lawn management patterns interact in a watershed and implications they may have for retaining and exporting nutrients from the soil environment.

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Table 2.1. Number of lawns sampled per site selection category.

	Density Level	Age Category		
		1986-2006	1936-1985	pre-1935
Hydro Group A	High	3	3	4
	Medium	4	3	4
	Low	4	4	4
Hydro Group D	High	4	4	4
	Medium	3	4	3
	Low	4	3	3

Table 2.2. Independent variables used in regression analysis per urban intensity metric for each of the five soil quality indicators.

Dependent Variables	Data Type	Independent Variables
<u>Model Set – Population Density</u>		
MBC-PD	Binary	Fertilizer (Currently Use - Y/N)
MBN-PD	Continuous	Log ₁₀ Lawn Age
Respiration-PD		Log ₁₀ Population Density
PNM-PD		PC1 – Exchange capacity factor
PNN-PD		PC2 – Soil organic matter factor
		PC3 – (+) P, (-) %Silt+%Clay
<u>Model Set – Average Parcel Size (APS)</u>		
MBC-APS	Binary	Fertilizer (Currently Use - Y/N)
MBN-APS	Continuous	Log ₁₀ Lawn Age
Respiration-APS		Log ₁₀ APS
PNM-APS		PC1 – Exchange capacity factor
PNN-APS		PC2 – Soil organic matter factor
		PC3 – (+) P, (-) %Silt+%Clay

Table 2.3. Soil texture classification of 61 lawns in Chittenden County; values are the means (standard error) of particle size class.

Texture Class	N	Sand, %	Silt, %	Clay, %	Hydro Group
Sandy Loam	32	65.3 (1.3)	26.6 (1.3)	8.2 (3.1)	A
Loamy Sand	13	77.9 (0.5)	16.2 (0.8)	6.0 (1.3)	A
Loam	8	40.6 (3.2)	42.2 (2.0)	17.2 (7.0)	B
Silt Loam	7	33.1 (3.7)	56.6 (2.6)	10.3 (1.6)	B
Sandy Clay Loam	1	49.9	23.9	26.3	C

Table 2.4. Descriptive statistics of the soil properties and processes from residential lawns in Chittenden County, VT (*extractable, Modified Morgan extractant).

Variable	Mean	Median	SE	%CV	Min	Max
MBC, $\mu\text{g C g}^{-1}$	564.1	562.2	29.9	41.4	92.7	1308.5
Respiration, $\mu\text{g C g}^{-1} \text{ d}^{-1}$	10.5	9.7	0.7	52.9	2.0	26.6
MBN, $\mu\text{g N g}^{-1}$	44.5	44.1	1.8	32.0	18.9	91.1
PNM [‡] , $\mu\text{g N g}^{-1} \text{ d}^{-1}$	0.9	0.9	0.1	46.8	0.1	2.0
PNN [‡] , $\mu\text{g N g}^{-1} \text{ d}^{-1}$	0.9	0.9	0.0	42.3	0.1	1.9
Total C, g kg^{-1}	23.2	23.0	0.7	22.6	12.3	37.7
Total N, g kg^{-1}	1.6	1.6	0.1	24.7	0.8	2.5
C:N	14.7	14.5	0.2	12.0	11.0	18.6
OM, %	3.3	3.3	0.1	24.7	1.5	4.9
CEC, $\text{meq } 100\text{g}^{-1}$	7.3	6.7	0.3	34.0	3.4	16.0
Ca*, mg kg^{-1}	1065.3	916.0	69.8	51.1	290.0	2968.0
Mg*, mg kg^{-1}	111.4	109.0	7.9	55.1	23.0	360.0
K*, mg kg^{-1}	53.3	52.0	2.8	41.2	22.0	145.0
Na*, mg kg^{-1}	13.1	12.0	0.7	42.9	7.0	42.0
S*, mg kg^{-1}	17.7	15.3	1.0	44.5	5.2	42.4
B*, mg kg^{-1}	0.2	0.3	0.0	60.6	0.0	0.5
P*, mg kg^{-1}	9.6	7.6	1.0	80.8	0.6	39.3
Al*, mg kg^{-1}	34.4	29.0	3.0	67.2	2.0	102.0
Fe*, mg kg^{-1}	5.8	3.6	0.6	80.7	0.8	23.3
Mn*, mg kg^{-1}	7.0	6.9	0.4	39.7	2.9	15.6
Zn*, mg kg^{-1}	3.6	2.0	0.6	127.2	0.3	24.2
Cu*, mg kg^{-1}	0.2	0.1	0.0	88.7	0.0	0.5
Ca saturation, %	70.0	75.5	2.3	25.5	21.7	92.8
Mg saturation, %	12.6	12.2	0.7	41.0	3.2	26.0
K saturation, %	2.0	1.8	0.1	43.2	0.9	5.3
Estimated BD, g cc^{-1}	1.4	1.4	0.0	11.1	1.0	1.7
pH _w	6.1	6.1	0.1	8.3	5.0	7.2

Number of observations: 61; else ‡ = 60

SE, Standard Error; %CV, Percent Coefficient of Variation; Min, Minimum value;

Max, Maximum value

Table 2.5. Pearson's correlation coefficients of soil particle size classes with soil quality indicators.

	MBC [†]	Respiration [†]	MBN [†]	PNM [‡]	PNN [‡]	TC [†]	TN [†]	C:N Ratio [†]
Sand, %	-0.44 [§]	-0.20	-0.44 [§]	-0.03	0.09	-0.34 ^δ	-0.52 [§]	0.41 [§]
Silt, %	0.42 [§]	0.31 [*]	0.36 ^δ	0.11	0.01	0.31 [*]	0.47 [§]	-0.36 ^δ
Clay, %	0.27 [*]	-0.20	0.43 [§]	-0.20	-0.31 [*]	0.22	0.39 ^δ	-0.34 ^δ

Number of observations: † = 61; ‡ = 60

Significance level of coefficients: * P ≤ 0.05; δ P ≤ 0.01; § P ≤ 0.001

Table 2.6. Pearson's correlation coefficients of soil properties with soil processes and urban explanatory variables.

	MBC [†]	Respir [†]	MBN [†]	PNM [‡]	PNN [‡]	Popn Den [†]	APS [†]	Lawn Age [†]	Fert [†]
%Silt+%Clay	0.44 [§]	0.20	0.44 [§]	0.03	-0.10	-0.14	0.23	0.13	-0.09
TC	0.38 ^δ	0.11	0.46 [§]	0.15	0.09	0.22	-0.14	0.40 ^δ	-0.35 ^δ
TN	0.46 [§]	0.10	0.54 [§]	0.07	-0.01	0.13	0.03	0.45 [§]	-0.24
OM	0.50 [§]	0.27 [*]	0.57 [§]	0.06	0.00	0.15	0.06	0.50 [§]	-0.26 [*]
CEC	0.22	0.11	0.37 ^δ	-0.20	-0.24	-0.02	0.15	0.22	-0.04
Ca	0.26 [*]	0.18	0.33 ^δ	-0.23	-0.24	0.02	0.10	0.16	-0.06
Mg	0.27 [*]	-0.06	0.37 ^δ	-0.15	-0.17	0.20	-0.04	0.27 [*]	-0.03
K	0.19	-0.18	0.36 ^δ	0.02	-0.09	-0.07	0.15	0.11	0.23
Na	0.37 ^δ	0.33 ^δ	0.23	-0.25	-0.22	-0.12	0.16	0.00	-0.16
S	0.21	0.20	0.30 [*]	-0.20	-0.20	0.09	0.09	0.14	-0.05
B	0.05	-0.01	0.04	-0.21	-0.18	0.25 [*]	-0.06	0.18	-0.24
P	-0.02	0.15	-0.19	-0.02	-0.01	0.16	-0.18	0.07	-0.13
Al	-0.24	-0.13	-0.29 [*]	0.09	0.06	-0.20	0.14	-0.19	0.08
Fe	-0.07	-0.08	-0.19	0.18	0.12	-0.34 ^δ	0.15	-0.34 ^δ	0.03
Mn	0.16	0.13	0.31 [*]	0.15	0.12	-0.06	0.02	-0.01	-0.16
Zn	-0.07	-0.08	-0.08	0.00	0.06	0.25 [*]	-0.24	0.23	-0.28 [*]
Cu	-0.05	0.09	0.02	0.07	0.12	-0.14	-0.06	-0.16	-0.16
pH _w	0.19	0.18	0.13	-0.23	-0.21	0.05	0.07	-0.05	0.00

Respir, Respiration; Popn Den, Population Density; Fert, Fertilizer Use

Number of observations: † = 61; ‡ = 60

Log₁₀ transformed variables: PopnDen, APS, LawnAge

Significance level of coefficients: * P ≤ 0.05; ^δ P ≤ 0.01; [§] P ≤ 0.001

Table 2.7. The retained principal components (PC) and their loadings (eigenvectors) from residential lawns in Chittenden County, Vermont (n=61).

	PC1	PC2	PC3
Proportion ϕ	0.37	0.16	0.09
Cumulative ℓ	0.37	0.52	0.61
Eigenvalue	6.63	2.81	1.56
%Silt+%Clay	0.31*	0.44*	-0.53 [§]
TC	0.11	0.94 [§]	0.08
TN	0.23	0.91 [§]	-0.09
OM	0.26	0.83 [§]	-0.08
CEC	0.86 [§]	0.22	-0.08
Ca	0.95 [§]	0.17	0.04
Mg	0.68 [§]	0.29	-0.24
K	0.52 [§]	0.11	-0.18
Na	0.25	0.10	-0.24
S	0.91 [§]	0.22	-0.01
B	0.66 [§]	0.30*	0.41*
P	0.36*	-0.22	0.69 [§]
Al	-0.69 [§]	-0.07	-0.24
Fe	-0.50 [§]	-0.15	-0.19
Mn	0.12	0.25	-0.08
Zn	-0.10	0.10	0.72 [§]
Cu	-0.28	-0.15	0.19
pH _w	0.81 [§]	0.04	-0.03

ϕ Percent of variance explained by current linear combination over the variance in all the independent variables.

ℓ Cumulative percent of variance explained by current linear combination over the total variance in all the independent variables.

[§] High component loading values > 0.5

* Moderate component loading values > 0.3

Table 2.8. Multiple linear regression models for soil quality indicators with Population Density as an urban intensity explanatory variable.

Model	Variable	Estimate	P-value	
MBC-PD				
(n = 59)	Intercept	823.69	<0.0001	R ₂ 0.47
	Log ₁₀ LawnAge	118.08	0.04	*R ₂ 0.43
	Log ₁₀ PopnDen	-137.26	<0.01	
	PC1 – (+) CEC, pH	64.43	<0.01	
	PC2 – (+) OM	90.93	<0.01	
MBN-PD				
(n = 60)	Intercept	63.81	<0.0001	R ₂ 0.50
	Log ₁₀ PopnDen	-6.34	0.02	*R ₂ 0.48
	PC1 – (+) CEC, pH	3.91	<0.01	
	PC2 – (+) OM	8.49	<0.0001	
Respiration-PD				
(n = 61)	Intercept	12.43	<0.0001	R ₂ 0.11
	Fertilize	-3.60	0.01	*R ₂ 0.09
PNM-PD				
(n = 60)	Intercept	0.71	<0.0001	R ₂ 0.20
	Fertilize	0.29	0.01	*R ₂ 0.15
	PC1 – (+) CEC, pH	-0.10	0.05	
	PC2 – (+) OM	0.11	0.04	
PNN-PD				
(n = 60)	Intercept	0.90	<0.0001	R ₂ 0.06
	PC1 – (+) CEC, pH	-0.10	0.05	*R ₂ 0.05

Popn Den, Population Density

Significance level of $p \leq 0.5$

*R₂, Adjusted R₂ value

Table 2.9. Multiple linear regression models for soil quality indicators with Average Parcel Size (APS) as an urban intensity explanatory variable.

Model	Variable	Estimate	P-value	
MBC-APS				
(n = 59)	Intercept	561.55	<0.0001	R ₂ 0.34
	PC1 – (+) CEC, pH	66.64	0.01	*R ₂ 0.32
	PC2 – (+) OM	102.12	<0.0001	
MBN-APS				
(n = 60)	Intercept	43.66	<0.0001	R ₂ 0.50
	PC1 – (+) CEC, pH	3.82	<0.01	*R ₂ 0.47
	PC2 – (+) OM	7.79	<0.0001	
	PC3 – (+) P, (-) %Silt+%Clay	-2.82	0.02	
Respiration-APS				
(n = 61)	Intercept	12.43	<0.0001	R ₂ 0.11
	Fertilize	-3.60	0.01	*R ₂ 0.09
PNM-APS				
(n = 60)	Intercept	0.71	<0.0001	R ₂ 0.20
	Fertilize	0.29	0.01	*R ₂ 0.15
	PC1 – (+) CEC, pH	-0.10	0.05	
	PC2 – (+) OM	0.11	0.04	
PNN-APS				
(n = 60)	Intercept	0.91	<0.001	R ₂ 0.08
	Log ₁₀ APS	-0.18	0.03	*R ₂ 0.06

Significance level of $p \leq 0.5$

*R₂, Adjusted R₂ value

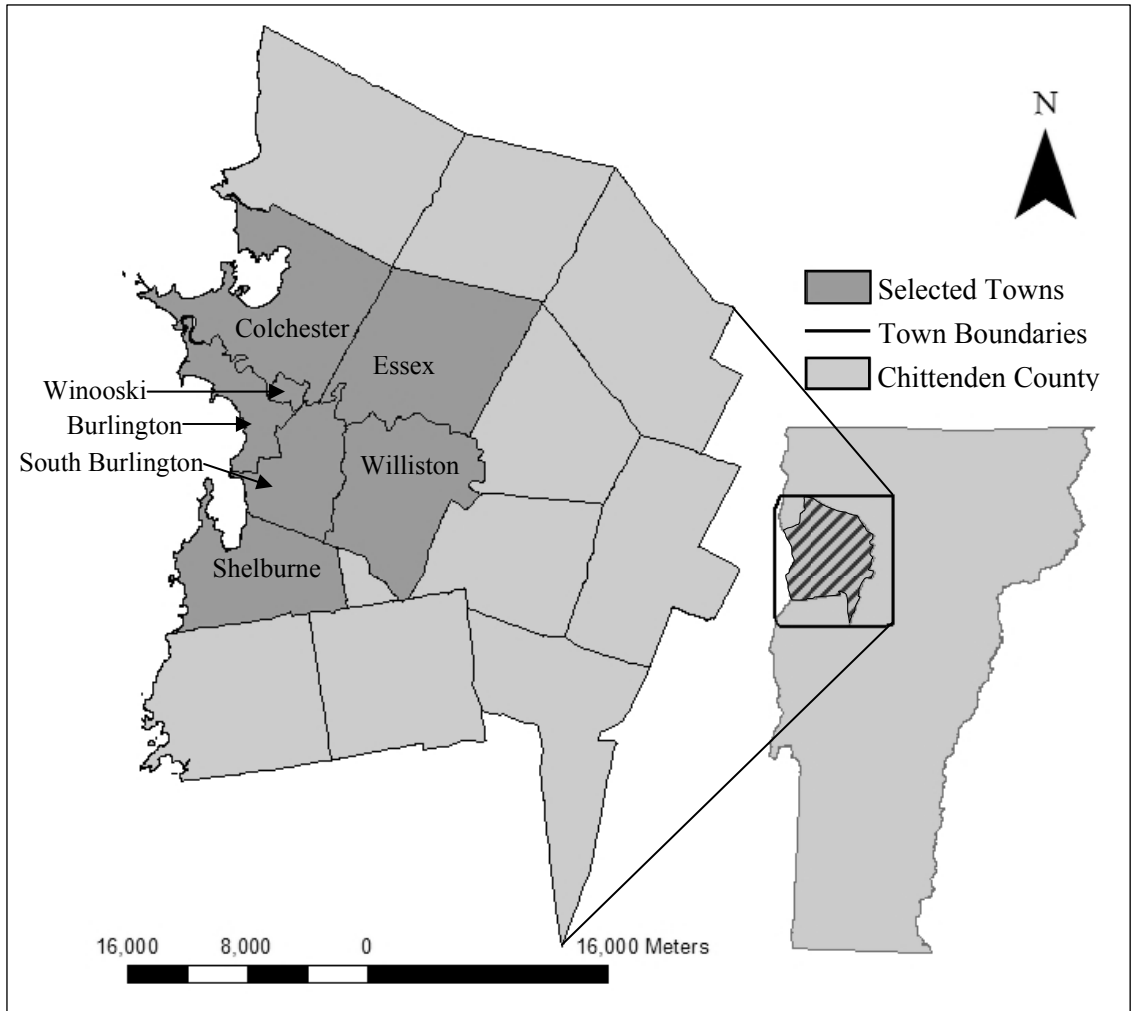


Figure 2.1. Towns selected for sampling in Chittenden County, VT.



Figure 2.2. Three levels of urban density used in site stratification.

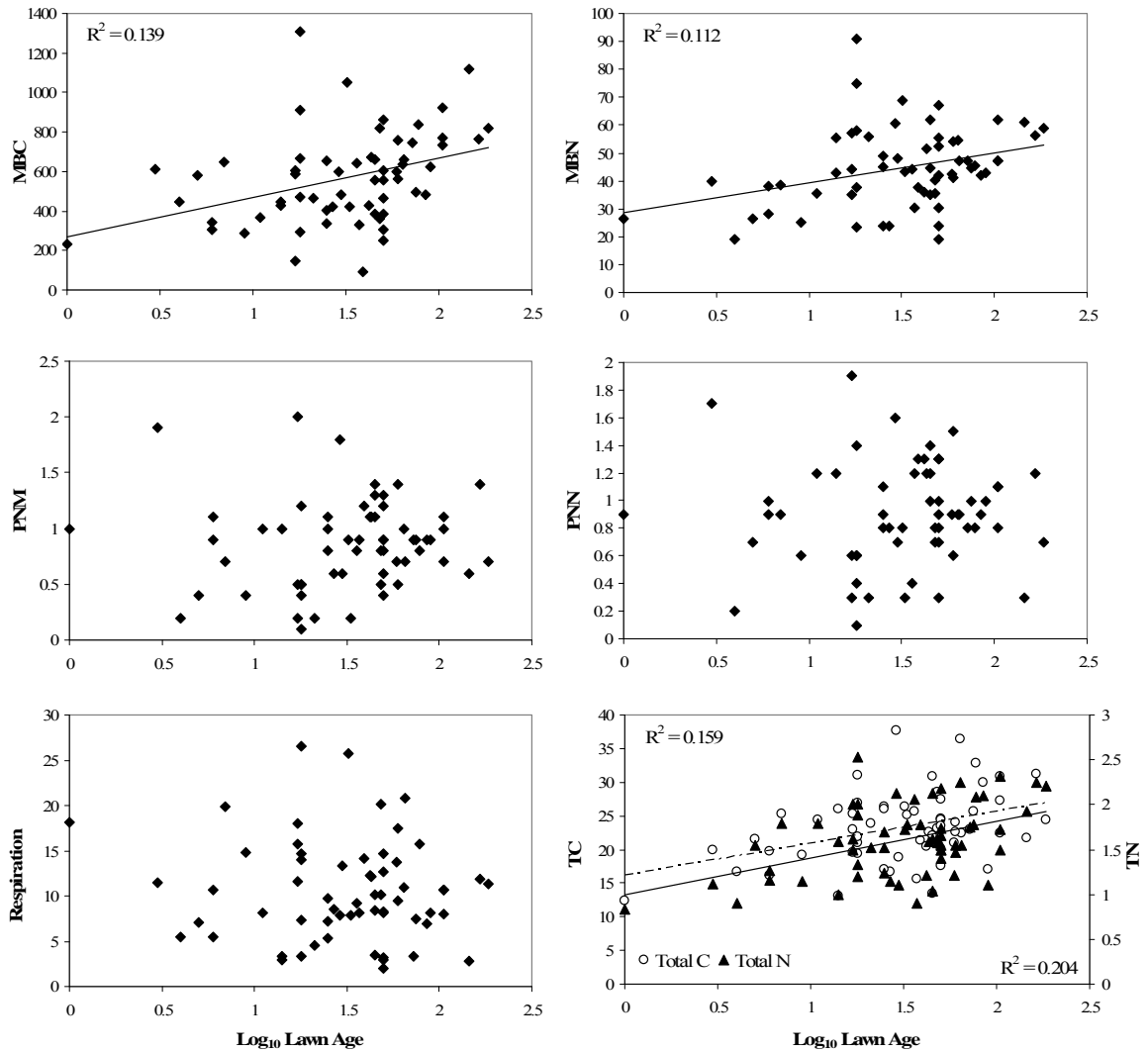


Figure 2.3. Relationship between soil quality indicators and Log_{10} Lawn Age (n=61, except PNM and PNN with n=60; R^2 values reported for significant correlations, p-value 0.05)

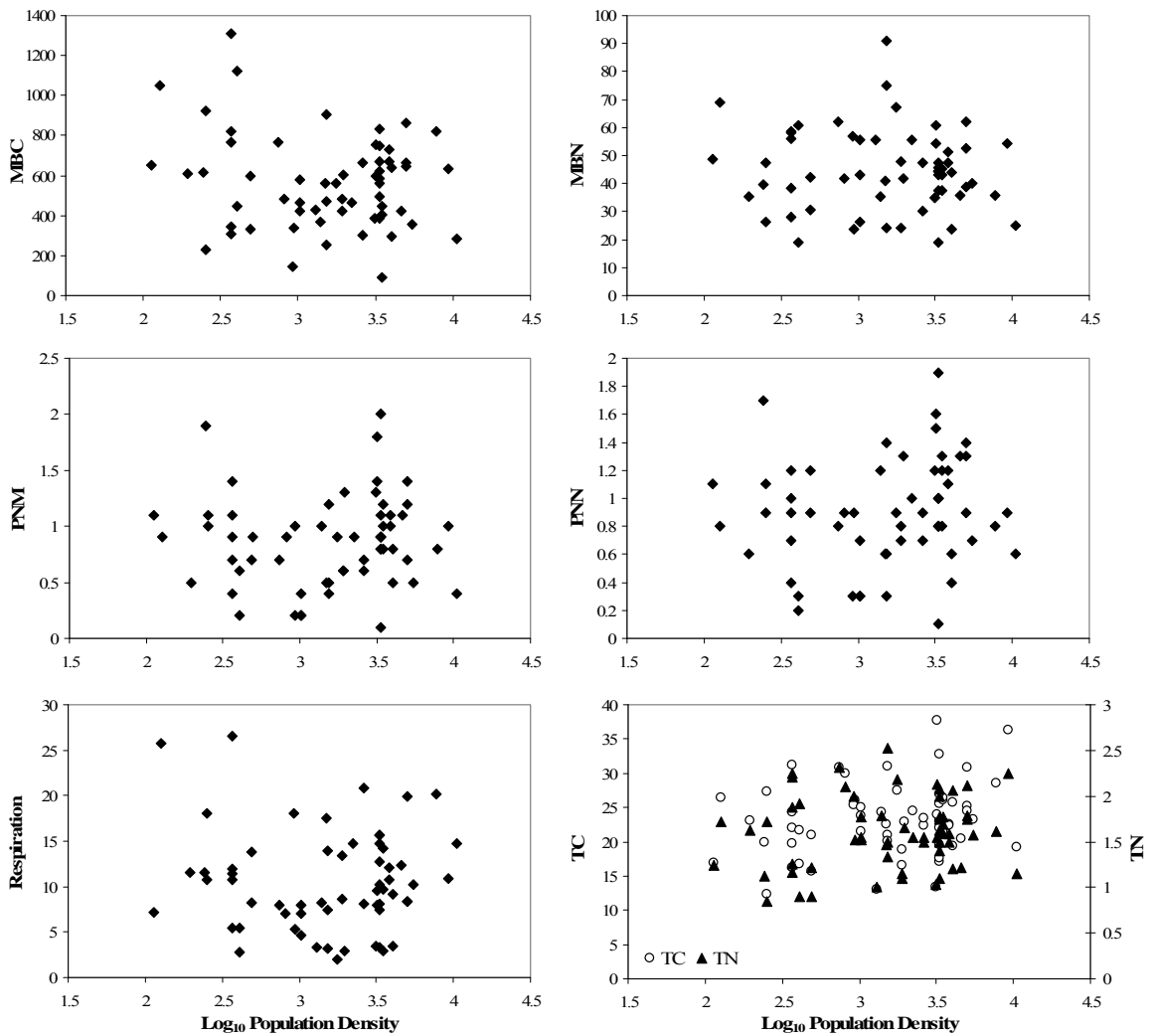


Figure 2.4. Relationship between soil quality indicators and Log_{10} Population Density (n=61, except PNM and PNN with n=60).

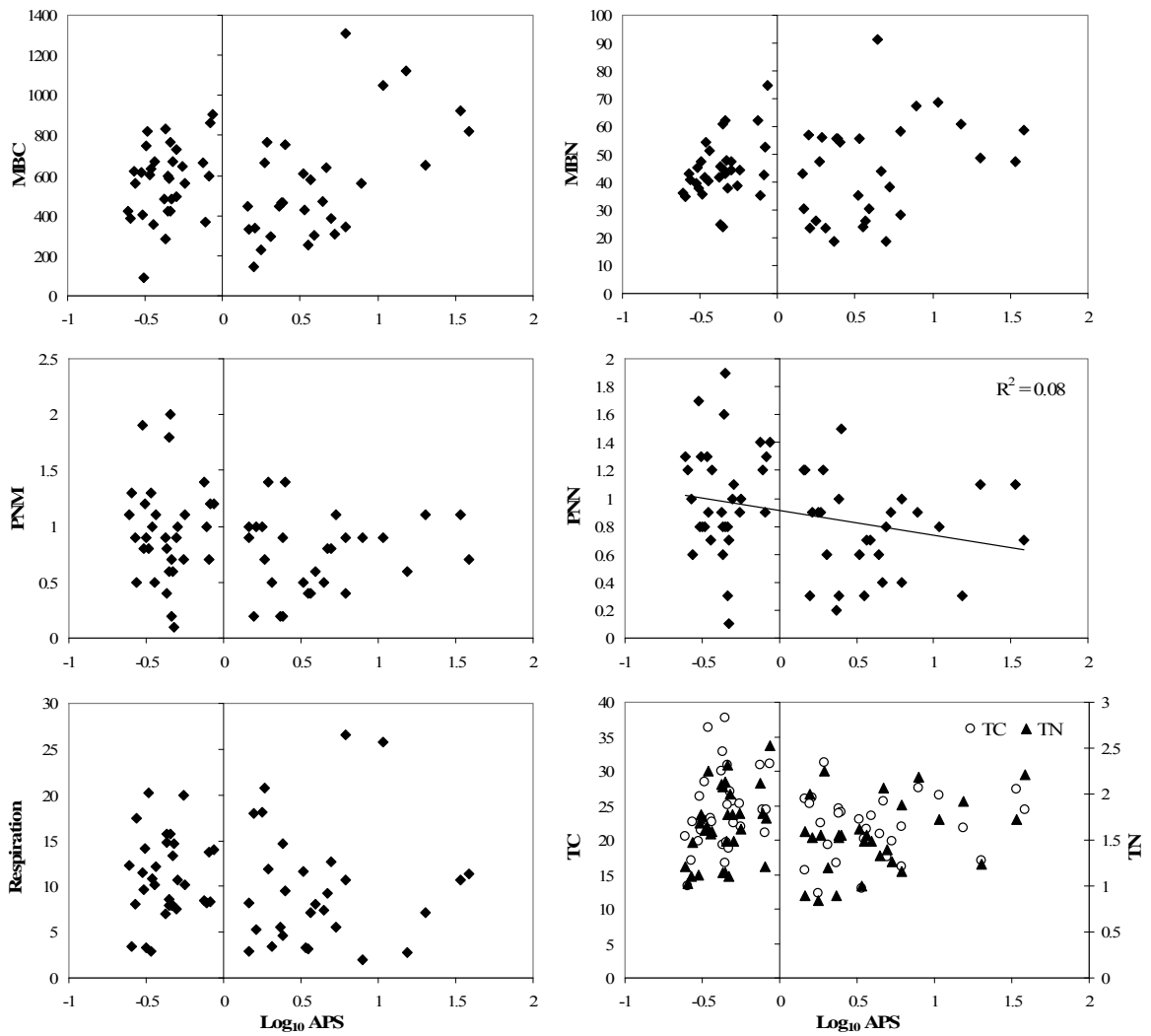


Figure 2.5. Relationship between soil quality indicators and Log₁₀ Average surrounding Parcel Size (APS; n=61, except PNM and PNN with n=60; R² values reported for significant correlations, p-value 0.05).

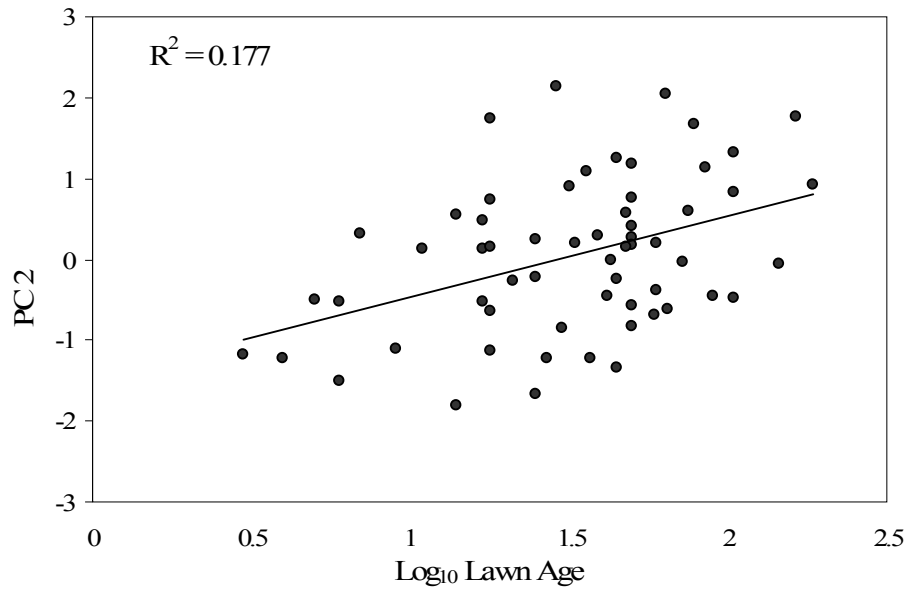


Figure 2.6. Relationship between PC2, soil organic matter component, and Log₁₀ Lawn Age (n=61).

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APPENDIX A – HOMEOWNER LAWN CARE SURVEY

SECTION A — *Fertilizer*

1. Do you employ a professional lawn care service?
2. Can you recall the name of the company that you employ?
3. Is there a specific lawn care plan or program that you pay for through the lawn care company for example gold service, master service plan?
4. From the following list, what services are provided to you by the professional lawn care company you employ
 - Mowing
 - Lawn fertilization
 - Lawn weed control
 - Tree and shrub care
 - Lawn insect/disease control
 - Liming/Lime application
 - Other, please specify. _____
5. Do you, or someone else other than a lawn care company apply fertilizer to your lawn
6. Do you, or someone else other than a lawn care company apply a dry, liquid, or both types of fertilizer?
7. What size of bag of fertilizer do you, or someone else use?
 - Large size (40 lb)
 - Medium size (18 lb)
 - Smaller size (~10 lb)
 - other size, please specify _____
8. From the categories listed, how much dry fertilizer would you estimate is applied to your lawn at each application?
 - Half of a bag
 - Whole bag
 - Other, please specify _____
9. From the categories listed, how much liquid fertilizer would you estimate is applied to your lawn at each application?
 - Half bottle
 - Full bottle
 - Other, please specify _____
10. In the past 12 months, how often has fertilizer been applied to your lawn by yourself, lawn care company or someone else?

11. What months do you, someone else or lawn care company apply fertilizer?

CHECK ALL that apply.

- January April July October
- February May August November
- March June September December Don't Know

12. Can you recall the name of the product(s) used for fertilizing?

13. When you, someone else or lawn care company fertilizes your lawn, is the driveway, sidewalk or curb area swept after the fertilizer application?

SECTION B --- Mowing & Water

14. When you, someone else or lawn care company cuts your lawn, are the clippings, left on the lawn, bagged or something else?

15. Have you had your soil tested to see what type of fertilizer or lime is needed?

16. From the following list, what do you or someone else use water for outdoors?

- Washing the car
- Cleaning the sidewalk or driveway
- Watering your lawn
- Watering your garden
- Other, please specify _____

SECTION C – Study Results

17. Do you want to receive the soil test results of your lawn? Y / N

18. After the completion of the study, do you want to receive a summary of the study's results from the soil analysis? Y / N

19. After the completion of the study, do you want to receive a summary of the study's results from the lawn care survey? Y / N

SECTION D – Lawn Quality (to be estimated by technician at time of survey)

Estimated Square footage of PERVIOUS area: % Grass % Tree cover/other natural area

Total % pervious to impervious on parcel: %Pervious %Impervious

% Lawn Composition of Grass Type/Species: % of Composition Turf Species

Turf Appearance Score: _____ 1 – Green / 2 – Green/Brown / 3 - Brown

COMMENT:

Turf Coverage Score: _____ 1 – Highly Patched / 2 – Lowly Patched / 3 – Full Coverage

COMMENT:

APPENDIX B – GAS CHROMATOGRAPH: QUALITY CONTROL

This appendix provides auxiliary information regarding the quality control measures in relation to CO₂ sample storage. Two separate data sources provided information regarding the quality control of the gas samples that were stored from 6-8 months in sealed vials until analysis on a gas chromatograph (GC; Shimadzu GC-17A, ECD sensor) optimized for the analysis of greenhouse gases including CO₂.

1. Three check standards were created on each day of gas sampling for quality control of the stored samples. The check standards were made by taking a gas sample from a tank of known concentration, 5000 ppm of CO₂ with a N₂ balance (Scott Specialty Gas). Samples of room air were also taken during the time of CFIM sampling. Both the room air and check standards were analyzed on the GC the same day as the corresponding incubation's gas samples. Both the room air and check standards were analyzed on the GC the same day as the corresponding incubation's gas samples. The resulting peak areas from the stored samples were significantly lower than known standards that were placed in vial and analyzed the same day. A 'fresh' 5,000 ppm had an average peak area of 136,508 however the check standards were returning an average peak area of 62,992 (Figure B.1.). In addition, vials of room air that were stored and run on the GC were returning an average peak area of 6,766 when a direct injection of room air into the GC produces a peak area of ~27,000 (Figure B.2.). Because of the lower recovery of the check standards and the room air analysis a storage experiment was conducted to test to identify a correction factor for adjusting the incubation data.

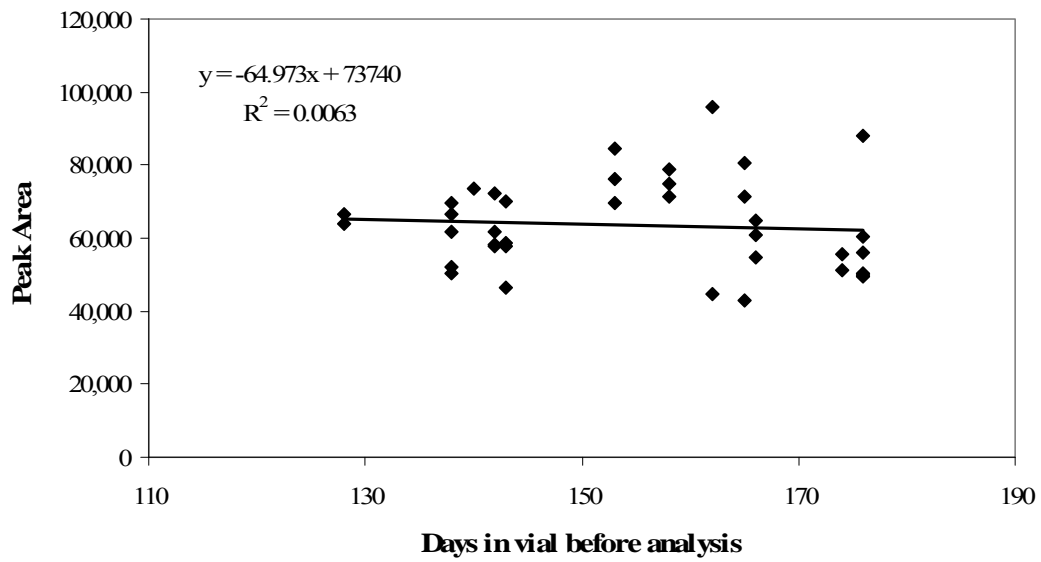


Figure B.1. Peak areas of 5,000 ppm check standards.

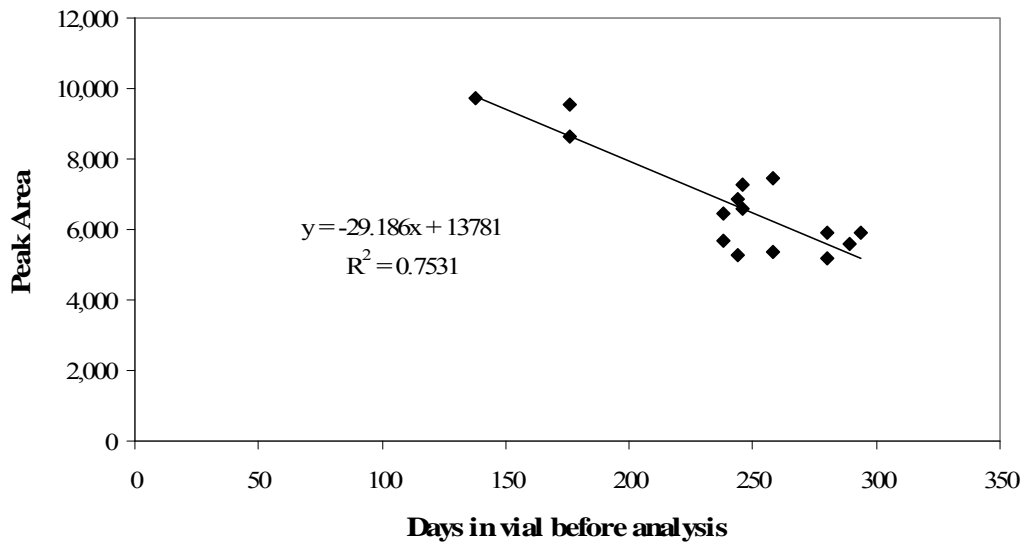


Figure B.2. Peak areas of room air samples.

2. A storage experiment was conducted to test the recovery of known concentrations after sample storage. Three replicate gas samples from five known concentrations: 1,000 ppm, 5,000 ppm, 10,000 ppm, 16,000 ppm, and 25,000 ppm CO₂ with a N₂ balance (Scott Specialty Gas). The samples were stored for 171 days in vials to simulate the length of time the CFI samples were stored until analysis. The resulting peak areas from the stored samples were compared to the peak areas obtained from “fresh” standard samples that were analyzed placed in a vial and analyzed within 7 days (Table B.1.). All of the standards were subjected to the same procedure of insertion of gas sample into vial and procedures for analysis on GC.

Table B.1. Storage test of samples stored for 171 days until analysis to determine percent recovery.

CO ₂ concentration (ppm)	Stored Standard		Fresh Standard		Recovery ratio (Stored/Fresh)
	Peak Area	N	Peak Area	N	
1,000	19,455 (5,153)	3	50,445 (12,648)	11	39%
5,000	81,051 (16,567)	2	136,508 (12,495)	17	59%
10,000	119,251 (13,172)	3	213,413 (12,429)	19	56%
16,000	179,527 (12,859)	3	265,829 (15,768)	18	68%
25,000	241,469 (4,131)	3	328,588 (24,177)	13	73%

Results from room air samples and storage test suggest that vial is losing gas not gaining as the room air samples contained less CO₂ than a peak area response from direct injection of room air. Furthermore, the results of the storage test identify that there was not a temporal trend but a concentration trend in the percent of CO₂ recovered after storage (Table B.1., Figure B.3.). The equation derived from the relationship between the peak area of stored samples to the percent recovery ratio (Figure B.3.) was used to

calculate a predicted recovery based on concentration for both the soil respiration and microbial biomass carbon samples (Table B.2.). The sample peak area was adjusted further with the corresponding method standard curve that was created the day of GC analysis from standards of known concentrations.

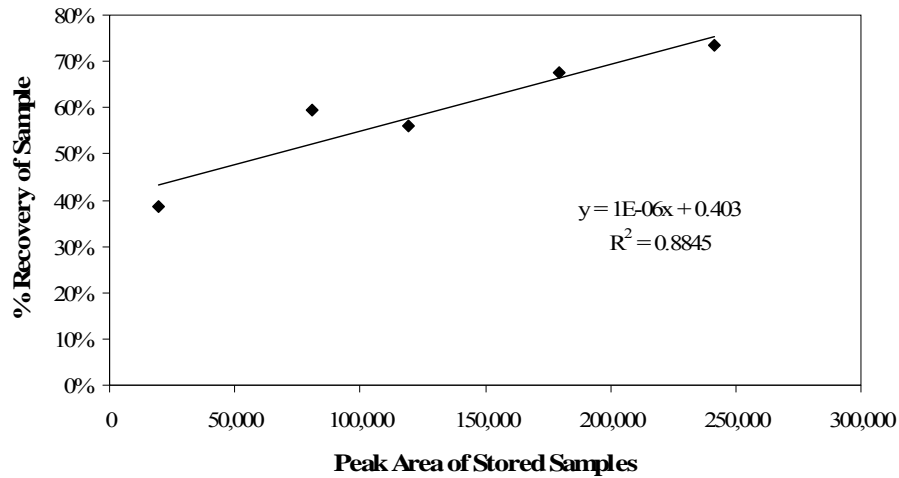


Figure B.3. Percent recovery of CO₂ standards after 171 days stored in vials.

Table B.2. Example of corrections applied to CFIM CO₂ samples.

Original Peak Area	Predicted Recovery Ratio*	Adjusted Peak Area†	Applied Method Standard Curve	Adjusted PPM	Original PPM
46,775	0.45	103,997	$y = 4E-05x^{1.5626}$	2,765	645

*Recovery equation: $y = 1E-06x + 0.403$

†Adjusted peak area = peak area/individual recovery ratio

APPENDIX C – DATA: BIVARIATE PLOTS

This appendix contains scatter plot matrices that depict the bivariate relationships of variables in this dataset to provide additional clarification on correlations between variables. The following figures provide bivariate plots for the soil quality indicators (MBC – microbial biomass carbon; MBN – microbial biomass nitrogen; PNM – potential nitrogen mineralization; PNN – potential net nitrification), urban metrics (PopnDen - Log_{10} Population Density; APS – Log_{10} Average Parcel Size; LawnAge – Log_{10} Lawn Age, Fertilize – Fertilizer Use (Y - 1.0, N - 0.0)), individual soil properties (%Silt+%Clay; OM, Ca, Mg, K, CEC, Na, S, B, Available P, available Al, Fe, Mn, Zn, Cu, pH, TC, TN), and the significant principal components representing the soil properties (PC1, PC2, PC3) across all lawn soils (n=61).

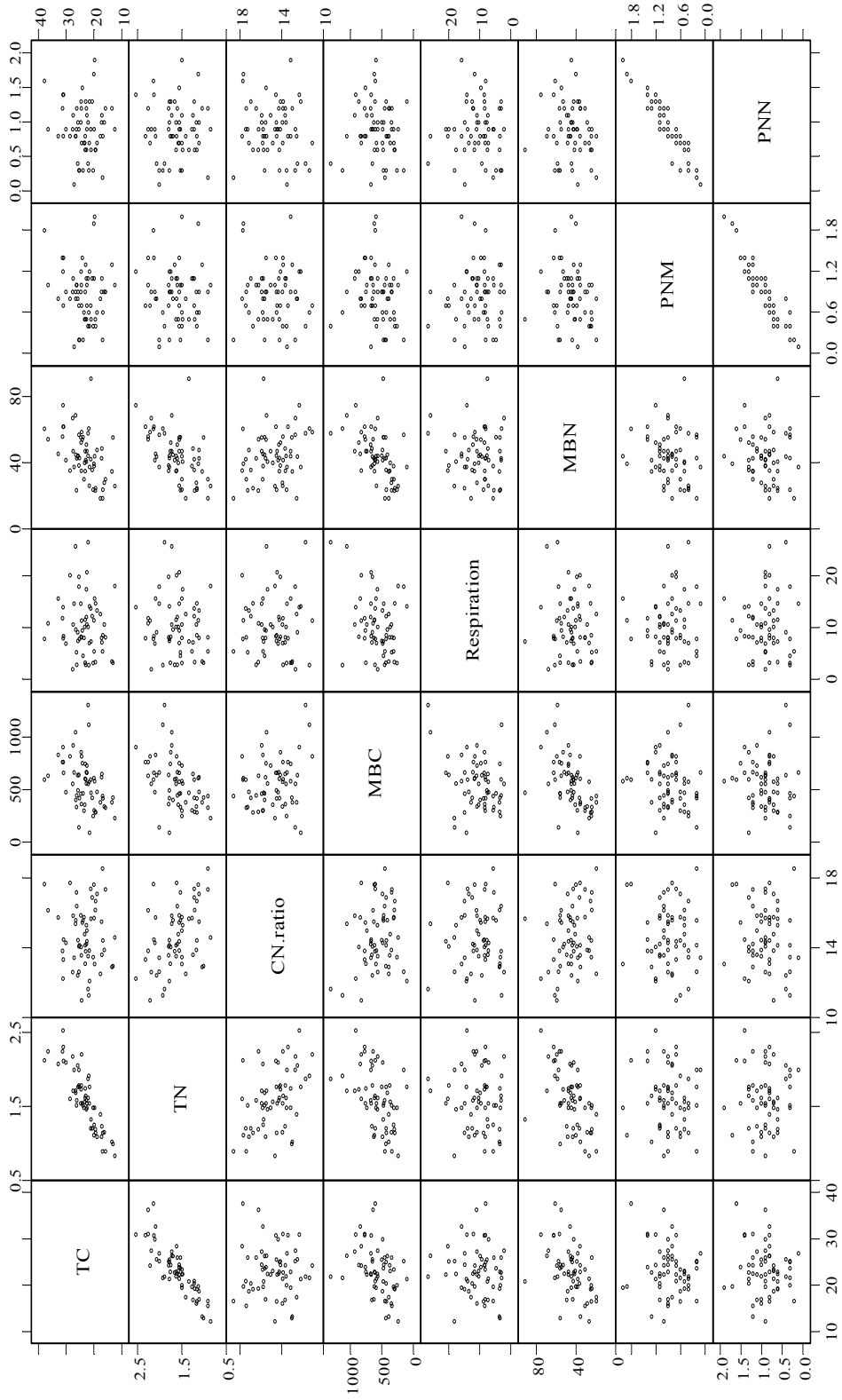


Figure C-1. Satterplot matrix of soil quality indicator variables.

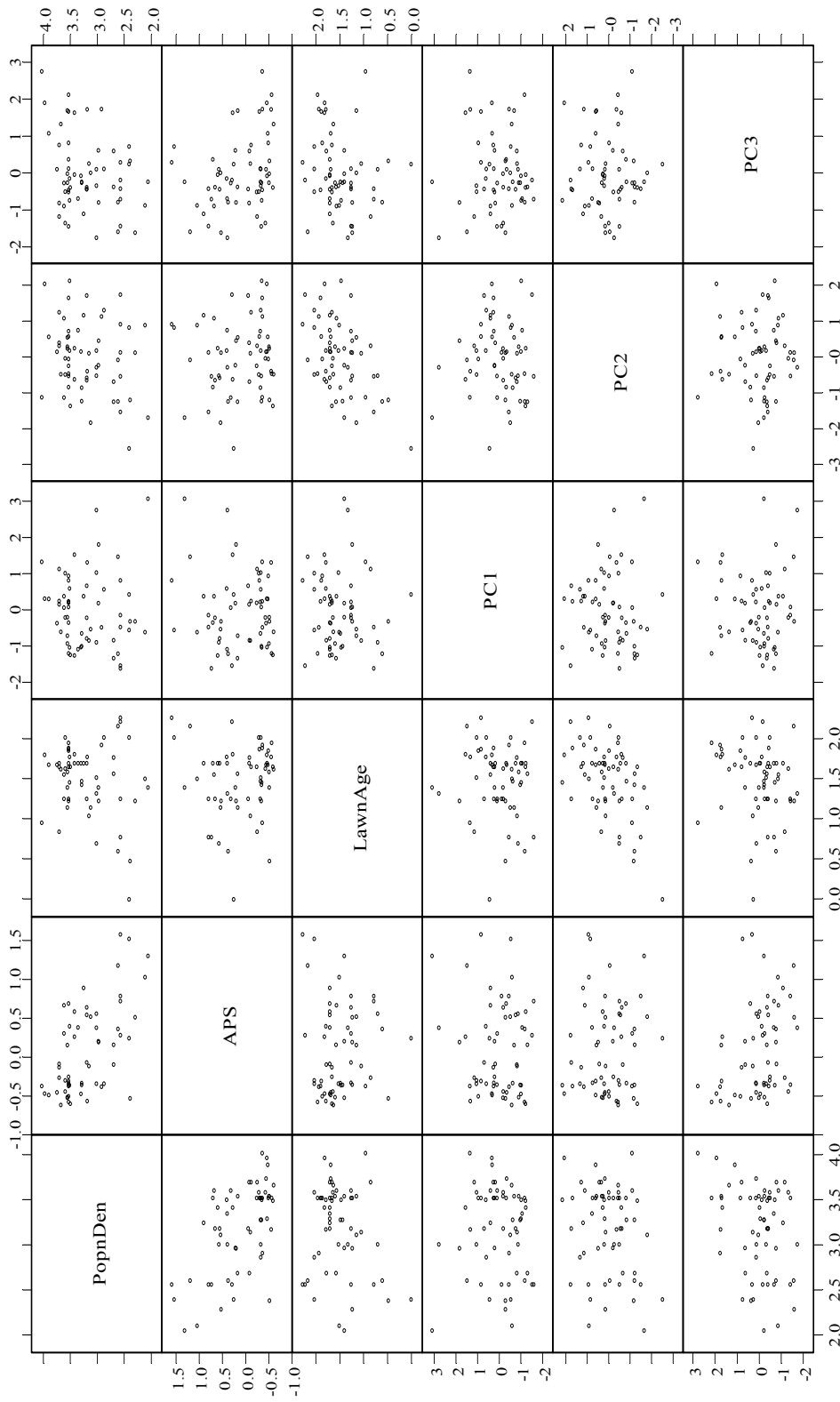


Figure C-2. Satterplot matrix of independent variables used to predict soil quality indicators in multivariate regression analysis (Log₁₀ transformed: PopnDen, APS, LawnAge).

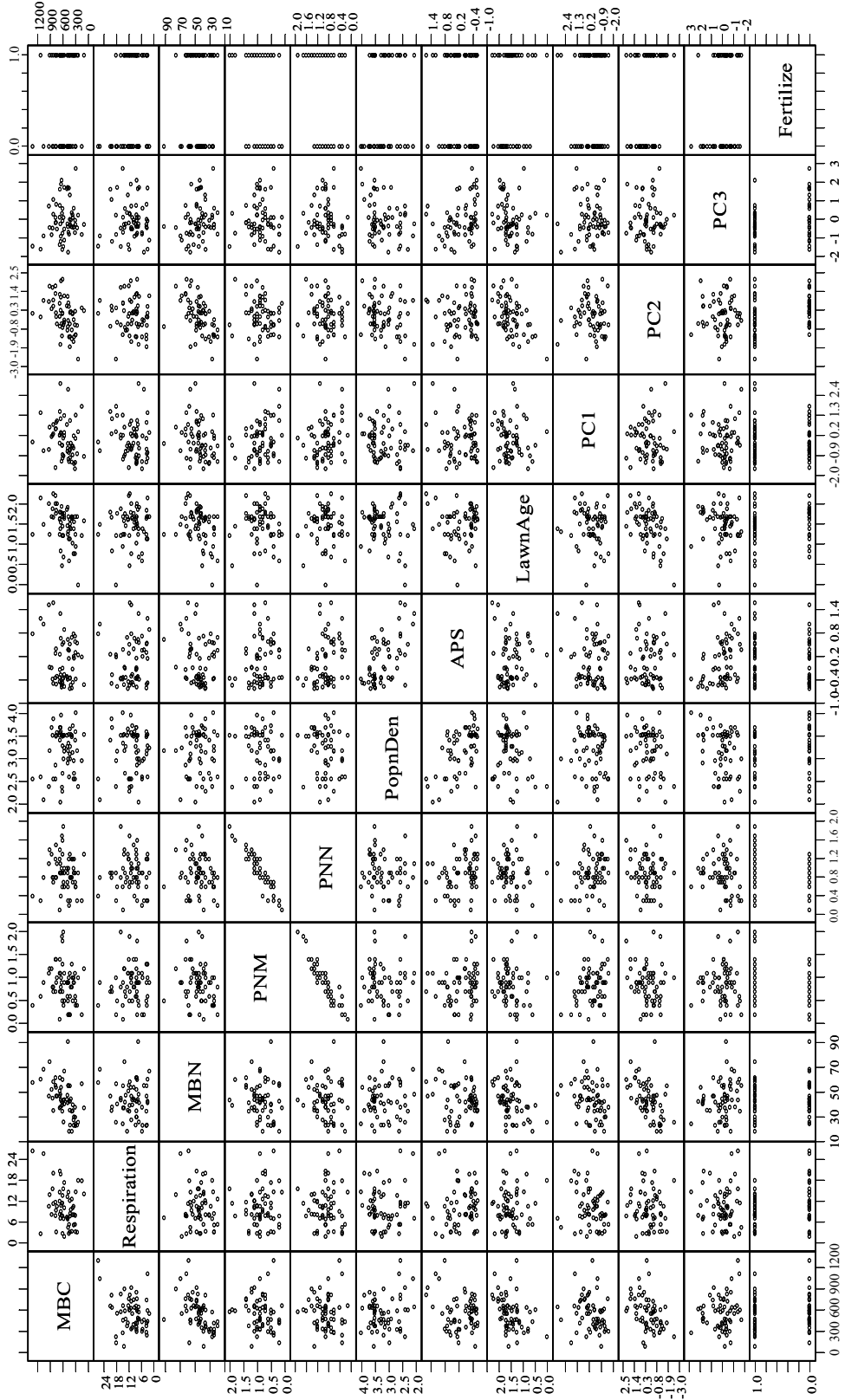


Figure C-3. Scatterplot matrix of independent and dependent variables used to multivariate regression analysis (Independent variables: MBC, Respiration, MBN, PNM, PNN; Dependent variables: PopnDen, APS, LawnAge, PC1, PC2, PC3, Fertilize).

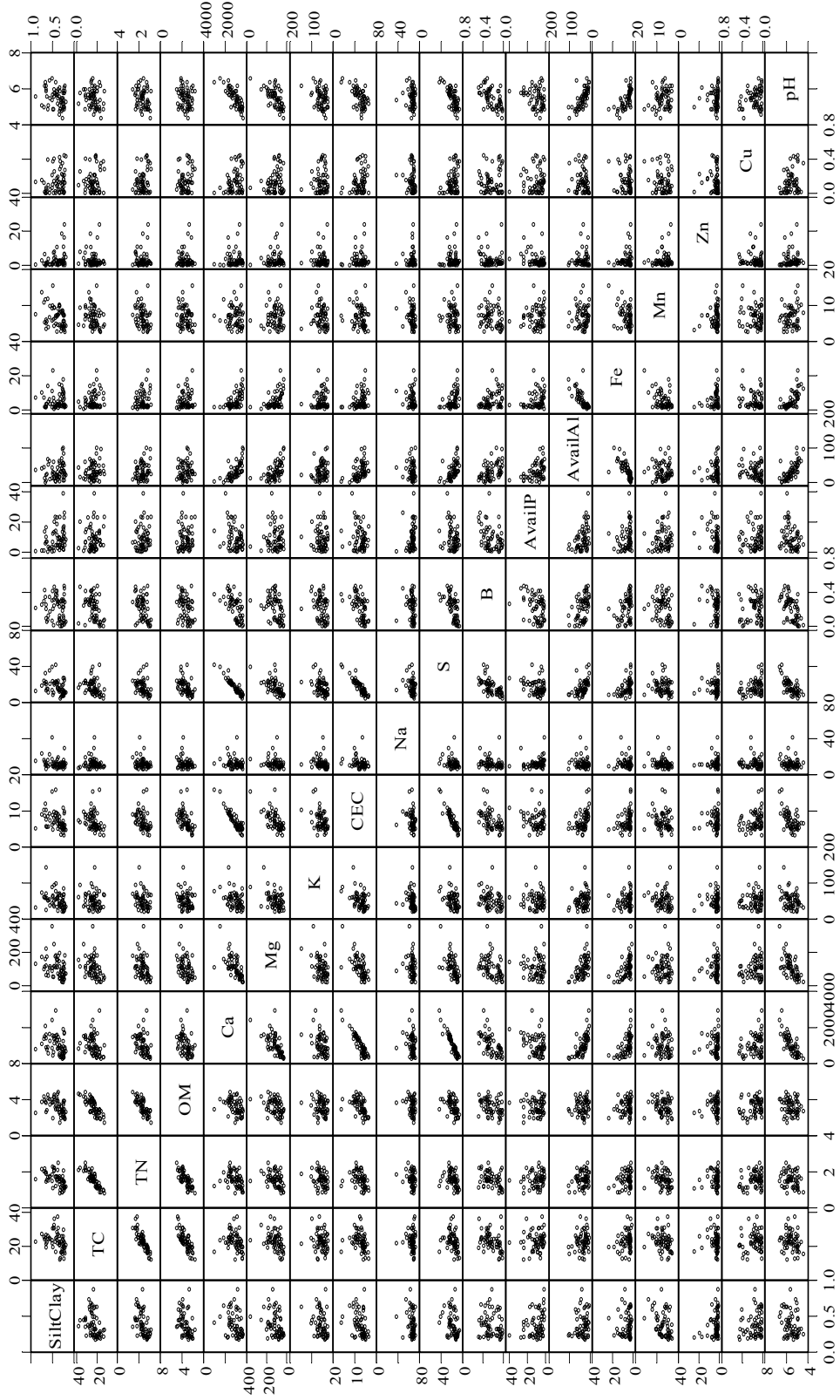


Figure C-4. Satterplot matrix of soil properties used in Principal Components Analysis.

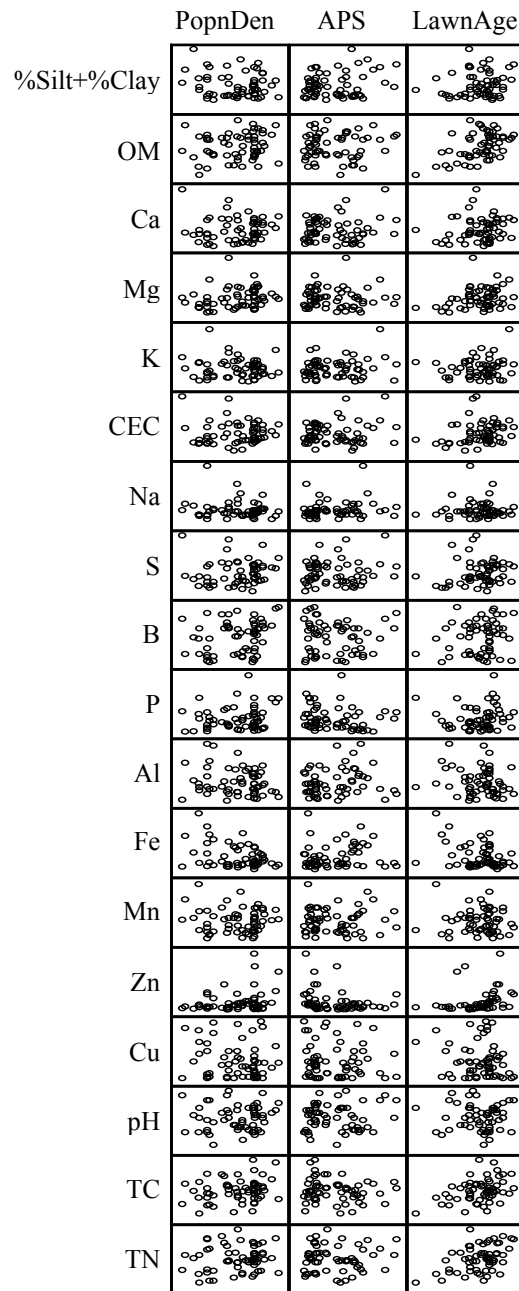


Figure C-5. Satterplot matrix of the urban metrics with the soil properties used in Principal Components Analysis.

APPENDIX D – SAMPLING INTENSITY

The following tables provide information regarding the sampling intensity from within each site selection class. After assigning the specific category of site selection variables (age of household, population density, hydro group) to each household in the study area, the households were summarized into respective categories (Table D.1). This dataset was randomly sampled to select 30 households; these households were sent a mailing for study participation. The year the house was built was collected from public records and for many towns had to be converted into a digital form. A small portion of the mailings were returned (Table D.2) due to instances where errors in data processing did not correctly match the housing point to an existing address or the property was currently vacant. Burlington and Winooski, classified as high density, were mainly classified as sandy or coarse-textured soils likely corresponding to sandy deltas deposited during the Champlain Sea. Therefore some of the categories for hydro group D had very few sites available in the study area and hydro group C sites were added to these categories.

Table D.1. Total number of potential households per site selection stratum.

	Density Level	Age Category		
		1986-2006	1936-1985	pre-1935
Hydro Group A	High	116	449	2485
	Medium	665	2769	1956
	Low	1126	2110	906
Hydro Group D	High	36	99	392
	Medium	128	473	99
	Low	2049	1057	323

Table D.2. Total number of returned mailings per site selection stratum.

	Density Level	Age Category		
		1986-2006	1936-1985	pre-1935
Hydro Group A	High	3	3	5
	Medium	0	1	1
	Low	2	3	2
Hydro Group D	High	8	0	1
	Medium	4	5	9
	Low	2	3	3

As discussed in Chapter 2, these designations of hydro groups were used to guide sampling as we hypothesized that development likely wiped out these hydro group differences during site preparation when fill could be brought in. We recognize that if we correctly sampled soil hydro group D, we would need to adjust the data for the sampling intensity of each strata (Table D.2) as the percent of the total population per category sampled varied creating a disproportionate random sample. However, the particle size analysis identifying soil texture of sites sampled (see Chapter 2) confirmed that the classified soil hydro groups from the 1974 Chittenden County soil survey did not correspond to the developed soil texture. For data analysis the measured soil texture was used in place of the hydro group classification as soil texture was found to be an important soil characteristic for the soil quality indicators.

Table D.3. Effective sampling rate from each stratum used for site selection.

	Density Level	Age Category		
		1986-2006	1936-1985	pre-1935
Hydro Group A	High	25.86	6.68	1.21
	Medium	4.51	1.08	1.53
	Low	2.66	1.42	3.31
Hydro Group D	High	83.33	30.30	7.65
	Medium	23.44	6.34	30.30
	Low	1.46	2.84	3.10