

NITROGEN AND CARBON BIOGEOCHEMISTRY IN SOIL AND  
VEGETATION ALONG AN INDIRECT URBAN-RURAL  
GRADIENT IN SOUTHEASTERN MICHIGAN

by

Ari Yaakov Kahan

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Thesis Committee:

Associate Professor William S. Currie, Chair  
Professor Daniel G. Brown



## Abstract

Within an urbanizing landscape, land is frequently set aside for the preservation of native communities and species. While land protection generally restricts immediate disturbances, subtle long-term effects are less well regulated. To evaluate the biogeochemical impacts which urbanization in the surrounding landscape has upon protected areas, 12 protected forest sites in Southeastern Michigan USA were stratified in an indirect urban-rural gradient and evaluated for overstory composition, ground-cover, and nutrient content in soil and foliage.

Within each site, overstory species composition and diameter at breast height were recorded, as were ground-cover and soil texture. Overstory basal area, total tree biomass, and foliar biomass were calculated. Soil and foliar carbon and nitrogen concentration and C/N ratio were sampled. Findings included a) a non-linear relationship between housing density and urban ecological impacts, b) an increase in housing density in the surrounding landscape positively correlated with an increased nitrogen concentration in forest soil, c) an increase in housing density positively correlated with an increase in overstory biomass. d) the region was highly nitrogen-rich, with a mean soil C/N ratio of 13.4, e) overstory biomass was a strong control on ground-cover, far more so than was the nitrogen content in soil. Results indicate that the halo of urban-ecological impacts exists in landscapes other than linear urban-rural gradients, and that the surrounding landscape has long-term impacts on soil and plant community composition in a protected area. Further exploration is required to determine the precise scale at which surroundings remain impactful.

## Acknowledgments

There passed a weary time. Each throat  
Was parched, and glazed each eye.  
A weary time! A weary time!  
How glazed each weary eye,

When looking westward, I beheld  
A something in the sky.  
At first it seemed a little speck,  
And then it seemed a mist ;

It moved and moved, and took at last  
A certain shape, I wist.

From *Rime of the Ancient Mariner*  
Samuel Taylor Coleridge, 1798

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## **Introduction**

The United States has a proud history of wilderness preservation, filled with popular icons such as Theodore Roosevelt, John Muir, and Aldo Leopold. Each of these early conservationists actively advocated for the protection of the nation's endangered areas. Among their accomplishments were the establishment of the national monument system, the founding of the Sierra Club, and the popularization of environmental literature. Due to these and similar efforts, wilderness protection went from a niche cause to a national ethic.

The author Wallace Stegner (1909 - 1993) was a similarly vocal proponent in the early battle to preserve American wilderness. Stegner worked to expand the national park system and famously fought dam construction at Dinosaur National Monument (San Francisco Public Library 2006). As an indicator of the author's impact, his 1964 "Wilderness Letter" was used to introduce the bill establishing the National Wilderness Preservation system. In this work, Stegner discussed the use of "wilderness as a genetic reserve, a scientific yardstick by which we may measure the world in its natural balance against the world in its man-made imbalance (Stegner 1969)." Wilderness protection was described as a way to defend the natural world against anthropogenic incursions. Thanks to the initiative of Stegner and other early actors, the preservation of native flora and fauna is a primary driver behind land protection and preservation.

Today, the World Resources Institute reports that 15.8 % of U.S. land is protected, or "dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means (World Resources Institute 2002)." Within the protected label, the level of actual protection varies

widely (Joppa et al. 2008). Protected land ranges from heavily-used city parks to restricted-access nature reserves, and includes the entire spectrum in-between.

This paper focuses upon protected terrestrial areas that receive relatively low levels of direct and recent human impact. As high levels of human activity are associated with changes in ecosystems (Blair & Launer 1997; Donnelly & Marzluff 2004; Alberti 2005; Duguay et al. 2007), low levels of direct impact make these sites an important element of conservation planning (Burger & Gochfeld 1998; Piessens et al. 2005). Yet, minimizing direct impacts is insufficient to fully protect many sites. There is an increasing awareness of the important relationship between protected areas and their surrounding landscapes (Matlack 1993; McKinney 2002; Pouyat et al. 2007).

While direct anthropogenic impacts are minimized in many protected areas, indirect impacts from the surrounding landscape may still encumber efforts at ecosystem preservation (Williams et al. 2006). Increased housing development in the rural landscape has produced proximate human impacts in previously isolated areas (Hansen et al. 2005). Hydrologic, biogeochemical, and atmospheric resources are shared between protected areas and their surrounding landscapes (Forman 1995). Modification of the surrounding landscape affects these shared resources and potentially impedes ecosystem conservation (Turner & Meyer 1993; Forman 1995; Thompson & DeGraaf 2001).

Conversion to residential land-use, which is a specific modification of the surrounding landscape, has previously been tied to changes in ecosystem processes (Lepers et al. 2005). At the extreme, urban settings have been linked to indirect impacts that include increased temperature, precipitation, and nutrient deposition (Botkin & Beveridge 1997; Gregg et al. 2003; Jenerette et al. 2006). These and similar urban effects can extend into



nearby protected areas and impede the preservation of native ecosystems (McDonnell & Pickett 1990; Alberti 2005; McKinney 2006). While the above correlations between residential land-use conversion and large-scale modifications of ecosystem processes are well documented, many others remain indistinct. Accordingly, there is a documented need for clarified linkages between changes in surrounding land-use and altered ecosystem function (Niemela 1999a; Andersson 2006; McKinney 2006).

One such void concerns the link between biogeochemical processes and urbanization. Pouyat (2007) argued that urbanizing areas have biogeochemical cycles that differ greatly from undisturbed ecosystems, but that the direction, magnitude, and extent of these differences are largely unknown. Documenting these differences is essential for the preservation of protected areas, as biogeochemical controls affect the plant and animal life extant (Schlesinger 1997; Aber et al. 1998).

To advance the understanding of biogeochemical processes in an urbanizing context, the present study was conducted in Southeastern Michigan, USA. Field and laboratory research was designed to explore carbon (C) and nitrogen (N) biogeochemistry within protected areas as a function of surrounding housing density. Vegetative components were also analyzed so as to explore the relationship between urbanization, carbon and nitrogen biogeochemistry in soils and plants, and plant community composition.

#### Subtle and Obvious Effects

Clarifying the potential pathways of influences that housing development has upon nearby protected areas is a first step towards understanding the interaction between urbanization and soil/vegetation biogeochemistry. These pathways have previously been divided into “obvious effect” and “subtle effect” categories (Russell 1993).

“Obvious effects” constitute those human activities that have clear *before* and *after* components. Within a typical park, examples include cutting paths through forests, clearing trees for fields, and other general management activities. Trampling, mowing, and collecting biological material cause immediate change to the form and function of the protected area. Due to their immediacy, obvious effects demand notice even when their source is unclear. During the 1960s, the weakening of avian eggshells was a sufficiently obvious effect to force environmental managers to track down the source (Russell 1993). While the sources were diffuse, the effects were obvious, and the pesticide Dichloro-Diphenyl-Trichloroethane (DDT) was banned. Generally, an interested observer can discover obvious effects by considering the *before* and *after* states of the system.

By contrast, the biogeochemical changes discussed in this paper are the results of “subtle effects” sensu Russell (1993). Subtle effects normally operate at long time scales relative to typical observation periods. Consequently, they cause ecosystem dynamics to be altered in ways that are not apparent initially because it is difficult to delineate *before* from *after*. Subtle effects are commonly accepted as status quo rather than as anthropogenically driven changes.

A typology has been proposed for considering four kinds of subtle effects (McDonnell & Pickett 1993): (1) “Indirect effects” introduce mechanisms that mediate currently functioning processes. These mechanisms might include an exotic competitor into a forest, or a new microbe in the soil. (2) “Historical effects” alter current behavior because of an earlier action. A typical example is land-use change such as a farm converted to a forest, where the low carbon content in former farm soil can alter ecosystem behavior for decades. (3) “Lagged effects” trigger impacts that take years to become apparent. An

example might be the build-up of estrogen in water supplies or chlorofluorocarbons (CFCs) in the atmosphere. (4) “Unexpected actions at a distance” are the effects of a far-away action as they cascade to affect a protected area. This might be second or third order results of a pollutant release or habitat destruction.

Subtle effect classes can be used as a framework for the study of urbanization effects upon protected areas. Alterations to biogeochemical cycles frequently result from mediation of existing ecosystem function, changes in historic land-use, compounding lagged effects, and distant actions. Lacking clear *before* or *after* states, biogeochemical changes can be pernicious, yet rarely inspire action. No single event serves as a catalyst for management activity. Further, biogeochemical changes are difficult to directly mitigate because of their scale, pervasiveness, and lack of controls on dominant drivers. Of particular concern, subtle effects can occur even as the protecting agency follows traditional best management practices. As will be shown in this paper, urbanization can subtly alter the biogeochemistry of a protected area even while other more obvious impacts are mitigated.

A better understanding of subtle urban effects on biogeochemistry would enable improved and proactive environmental management. At the present, the knowledge body is contradictory, disintegrated, and an inhibitor to effective management practices (Pickett et al. 2001). Further research, such as the present study, will help identify significant factors in the management of biogeochemical components of protected areas within the matrix of a greater landscape.

#### Patterns of Urban Expansion

Human demographic and dispersion patterns drive the need for a more complete understanding of the subtle effects of urbanization on the biogeochemistry of soil and

vegetation. The global population of humans is predicted to reach 7 billion in 2012 (Edwards 2008), with between 39% and 50% of the Earth's surface transformed or degraded by humanity (Vitousek et al. 1997). Within the United States, the population is both growing and decentralizing (Hansen et al. 2005; United States Census Bureau 2008), and more widespread urbanization expected to follow (Alberti 2005). Trends indicate population movement away from metropolitan centers and into low-density suburban and exurban developments (Hansen et al. 2005). Combined with tendencies towards larger residential lots and longer commutes (Vesterby & Heimlich 1991; Bram & McKay 2005), the extended national footprint of development guarantees human proximity for all but the most isolated protected areas.

In the year 1950, only 6% of counties in the conterminous United States (289,904 km<sup>2</sup>) were developed at a density of forty acres or less per home (Brown et al. 2005). By the year 2000, counties with densities of at least forty acres per home constituted 27% of the conterminous U.S. (1.48 x 10<sup>6</sup> km<sup>2</sup>) (Brown et al. 2005). Population growth in this period was accommodated by expanding the number of counties with 1-40 acres per house, rather than adding or intensifying urban counties (less than 1 acre / house). Consequently, in the year 2000, more than 50% of the population resided in low-density urban areas (Hansen et al. 2005). The rapid growth of low-density development has increased the number of natural areas with proximal human impact (Forys & Allen 2005; Theobald 2005).

Southeastern Michigan exemplifies the dispersion of the United States population across the landscape. According to US Census Bureau Data, in the 10 Michigan counties that comprise the Detroit, Ann Arbor, and Flint metropolitan areas, total households increased from 1.92 million to 2.08 million between 1990 and 2000. Although regional population

increased, the total number of households residing in the four major cities declined from 494,374 to 455,099. The disparity between the increase in regional population and the decrease in city population represents a shift from urban centers to lower density developments (Brown et al. 2008). Similar dispersal patterns are occurring across the country (Brown et al. 2005).

Patterns of housing development are significant to the present study due to the complex suite of biogeochemical effects associated with urbanization (Pouyat et al. 2007). Pouyat (2007) argued that the current understanding of factors affecting regional scale biogeochemical cycles is incomplete. Specifically, the intricate relationship between urbanization and nitrogen in soil and vegetation is difficult to predict (Groffman et al. 2004; Groffman et al. 2006). In response, the present study focuses upon the connection between urbanization and patterns of nitrogen in soil and vegetation at the landscape scale.

The remainder of the introduction discusses the relationship between the biogeochemical nitrogen cycle, human, and plant communities. A conceptual framework is provided concerning the movement of nitrogen from the surrounding landscape into a protected area, and the potential subsequent alterations of protected plant communities. Ultimately, anthropogenic nitrogen contributions are connected to urbanization.

#### Nitrogen – An Anthropogenic Pollutant

Human actions, such as housing development, are thought to alter landscape-level biogeochemical nitrogen (N) cycles (Galloway et al. 2003). Nitrogen is frequently the limiting element in terrestrial ecosystems (Vitousek et al. 1997), and N availability is often a determinant of ecosystem composition and productivity (Marshall & Porter 1991; Freedman et al. 1996; Schlesinger 1997). N limitations exist because the N available through natural

means such as atmospheric deposition or biological N fixation is significantly below the potential uptake of most terrestrial systems (Asner et al. 1997).

Human actions can contribute N to previously N-limited systems (Vitousek et al. 1997), with artificial nitrogen fixation and fossil fuel combustion contributing to an unprecedented accumulation of reactive N in the environment (Galloway et al. 2003). Worldwide, annual reactive N production from fertilizer manufacture (the Haber-Bosch process) is approximately 100 Tg, with annual vehicle, power plant, and related emissions estimated at an additional 25 Tg (Galloway et al. 2003). In total, human contributions have roughly doubled the annual rate of nitrogen inserted into the terrestrial nitrogen cycle (Asner et al. 1997; Vitousek et al. 1997).

Denitrification, or the process through which N is converted to a gaseous form, has not increased at a rate equivalent to artificial nitrogen fixation (Galloway et al. 2003). With total N fixation and denitrification no longer equivalent, excess reactive N now accumulates in some environmental reservoirs (Galloway et al. 2003). Through hydrologic pathways such as surface runoff and subsurface leaching, excess nitrogen can reach and accumulate in systems downstream from terrestrial systems that receive anthropogenic N inputs (Aerts & Berendse 1988; Ju et al. 2004; Fisher et al. 2007). Introduction of N from the surrounding landscape to nitrogen-limited protected areas is a serious concern (Aber et al. 1989; Aber et al. 1995). As an example of this concern, the United States Environmental Protection Agency classifies reactive N as a pollutant due to its contribution towards “nutrient overload” in terrestrial systems (US EPA 2008).

The accumulation of N in unintended environmental locations such as protected areas is a significant and subtle human impact. Carbon accumulation in soil and vegetation is

partially dependent upon nitrogen availability (Marshall & Porter 1991; Hungate et al. 2006). When additional N is available, N-limited vegetation often use it to increase primary productivity and amass additional carbon (Hungate et al. 2006). Limited nitrogen availability can inhibit both maximum photosynthetic rates and biomass accumulation in plants (Luo et al. 2004; Finzi et al. 2006; Bown et al. 2007). In an N-limited system, the rate of carbon fixation is thus linked to nitrogen availability (Vitousek & Howarth 1991; Asner et al. 1997; Aber et al. 1998; Kees-Jan van Groenigen et al. 2006). Correspondingly, stoichiometric C/N ratios in soil and vegetation are typically higher in N-poor systems than in N-rich systems (Marshall & Porter 1991; Gundersen et al. 1998b; Currie 1999; Blodgett et al. 2005; Pardo et al. 2006).

#### Nitrogen Dynamics within Protected Systems

Free reactive nitrogen poses a number of potential threats to protected ecosystems. As examples of threats, the effects of nitrogen upon community composition, resilience to exotic species and productivity are described below. These threats are presented as exemplars of the kinds of subtle effects which may counteract the aims of land protection agencies.

Within a protected system, N availability is a partial determinant of the growth rate of individual vegetative species (Olde Venterink et al. 2001; Henry et al. 2005; Kobe 2006), and of the species' consequent abilities to effectively compete (Lowe et al. 2003; Hangs et al. 2004). Plant species differ in their respective abilities to use additional N, with species that derive the greatest benefit being given a competitive advantage when anthropogenic N is introduced to a system (Hooper & Vitousek 1998; Olde Venterink et al. 2003). This advantage can allow high N utilizers to outcompete species that derive little benefit from

additional N, and can result in an N loaded system with an altered composition relative to the previously N-deficient system (Vaitkus et al. 1993; Wedin & Tilman 1996). Significantly, because the species that benefit from excess N are not necessarily the species that currently dominate, N addition can change the prominence of species within an ecosystem (Vitousek et al. 1997; Bernhardt-Römermann et al. 2007). This process can be abetted by accompanying changes in species specific biomass, which modify relative competitive capabilities (Aerts & Berendse 1988; Hager 2004).

As an example of nitrogen-driven community change, low terrestrial nitrogen levels were found to favor selection of short stature plants and perennials in Minnesota grasslands, while higher nitrogen levels led to the dominance of long-lived herbaceous and woody species (Tilman 1987). As shown in this example, N addition can alter plant community composition. In a protected area receiving nitrogen inputs from the surrounding landscape, such changes in composition could act counter to the goals of the managing agency.

Additional N inputs pose a second threat to protected ecosystems by potentially enabling the establishment of non-native species. Presence of exotic species is frequently correlated with high levels of soil nitrogen (Huenneke et al. 1990; Stohlgren et al. 1999). While the correlation between exotic species and nitrogen may be driven by many factors, it has been suggested that unexploited resources foster potential niches for new species (Davis et al. 2000; Levine et al. 2003; Burns 2004). Excess nitrogen in a protected area can open pathways for new species and a consequent alteration of the contained communities. Potential effects are varied, but degradation of the native community is a possibility (Mack et al. 2000).



The final threat discussed here, the relationship between community composition, nitrogen, and altered net productivity, is a complex issue with ongoing research (Mittelbach 2001; Kahmen et al. 2005; Kahmen et al. 2006; Ashton et al. 2008). While the above paragraphs have emphasized that N inputs are frequently associated with increased productivity in specific species (Niinemets & Kull 2005), a plant community whose composition is altered by additional N inputs may also undergo a net loss in productivity. Whether the productivity loss is attributed to a decrease in biodiversity (Tilman et al. 1997; Hector et al. 1999), loss of the most productive species (Symstad et al. 1998), or other factors (Cardinale et al. 2007), nitrogen inputs can correlate with decreased total productivity. In turn, decreasing a particular community's productivity can have effects including alteration of nearby community compositions and cascading extirpations of plant species (Freedman et al. 1996; Symstad et al. 1998; Wardle et al. 2004). N inputs, and their frequently surprising effects upon ecosystem composition and productivity, may cause undesirable changes within a protected area.

The three "threats" discussed here demonstrate how nitrogen can subtly counter the actions of land conservation agencies. Distant releases of nitrogen mediate ecosystem processes within the protected areas, while historic effects play a strong role in determining the potential interplay between additional N and current dynamics. A general lack of data on *before* states makes it difficult to decide whether an ecosystem has entered the *after* phase. Further, knowledge and data challenges make it difficult to even characterize differences between ostensible *before* and *after* phases. Fortunately, additional exploration of the relationship between nitrogen, carbon and urbanization is being conducted in a number of different contexts.

### Biogeochemical Cycles in Urban Areas

Past research has indicated that proper management of soil and vegetation biogeochemistry near dense population centers needs to incorporate factors which are distinct from management in isolated protected areas (Niemela 1999a). Similarly, a recent review of long-term urban-rural gradient research concluded that greater emphasis needed to be put upon building an anthropocentric model of biogeochemical controls (Kaye et al. 2006). An anthropocentric model of biogeochemistry, which could include factors such as impervious surface proliferation, urban atmospheric chemistry, and human-driven landscaping, might produce more significant predictions of soil nitrogen and carbon content in an urban context than traditional natural control models (Kaye et al. 2006). As discussed in this paper, the aggregate behavior of such built-environment controls could potentially be summarized by a landscape scale variable such as housing density.

The potentially significant effects of nitrogen on unmanaged ecosystems, along with increased human presence near protected areas, have fueled a number of long-term ecological studies on the effects of urbanization on biogeochemical cycles (Pouyat 1997; Baker et al. 2001; Groffman et al. 2004). These studies have been largely inconclusive regarding the interaction between urbanization in the surrounding landscape and nitrogen dynamics within protected areas (Groffman et al. 2006). While there has been consistent correlation between increased urbanization and increased N mineralization, in each case the results have been discounted due to confounding variables. Along the New York urban-rural gradient, a positive correlation between population density and N mineralization in forest stands was discounted due to earthworm activity (Pouyat 1997). Similarly, a positive correlation between net N mineralization and urban land-use in North Carolina was criticized for insufficiently accounting for urban heat island effects (Groffman et al. 2006; Pavao-

Zuckerman & Coleman 2006). Confounding variables, which are an inherent part of landscape-scale ecological research, have complicated the interpretation of urban-rural gradient research results.

While the same ecological processes govern urban and rural biogeochemical cycles, the relative importance of the processes differs along the urban-rural spectrum (Niemela 1999b). As an example, Groffman (2006) suggested that forest community composition and soil-atmosphere fluxes were more strongly influenced by exposure to urban atmospheric chemistry than by natural system controls (geology and soil parent material). Similarly, Pouyat (2007) reported that urban controls on soil moisture are significant predictors of N storage. The relative weighting of urban and natural controls along the urban-rural spectrum is an area of unexplored interest (Pickett et al. 2001), with consistent patterns of correlation between urbanization and nutrient biogeochemistry in soil and vegetation as an elusive goal (Pouyat et al. 2007).

This paper asks the broad question, “How does urbanization correlate with differences in soil nutrient chemistry and plant communities in protected areas?” It explores land-cover differences as a surrogate of urbanization, and questions whether higher housing density in the surrounding landscape correlates with increased nitrogen accumulation in protected areas. Ultimately, it asks, “Are protection efforts, which are generally geared towards inhibiting ‘obvious’ destruction of ecosystems, being thwarted by the ‘subtle’ effects of biogeochemical cycle alterations?”

## Research Questions

### Points of Interest

The research questions for this study were designed to address aspects of the relationship between urbanization and terrestrial nitrogen accumulation that have not yet been explored by the field. Five points of differentiation from previous research were incorporated: (a) geography, (b) built landscape structure, (c) measure of urbanization, (d) definition of protected area, and (e) choice of plant community measures.

Southeastern Michigan's particular combination of housing development patterns, terrestrial ecosystems, and climate differentiate this study's geography from previous urban-rural gradient studies. A state-wide literature search on urban-rural nutrient studies returned only 10 results, of which the majority were concerned with aquatic systems.<sup>1</sup> The omission of urbanization factors occurs despite more than one hundred papers published on nitrogen cycling in Michigan forests.<sup>2</sup> A brief review of relevant Michigan forest studies reinforces the knowledge gap; the preponderance of forest nitrogen studies were conducted in the rural northern portion of the state (Zak et al. 1989; Zak & Pregitzer 1990; Stottlemeyer & Toczydlowski 1999), rather than the more densely populated southern portion. Southeastern Michigan was conceived as an integral part of the current study, with its geography likely to provide new comparative data on both urbanization effects and regional nitrogen trends.

As the nitrogen cycle is locally self-similar, the distance between Southeastern Michigan and previous urban-rural studies is a valuable asset. The established long-term urban-rural research sites (Maryland, New York / Connecticut, and Arizona) are 1,000 – 3,000 km from the region. Further, a literature search indicates that few relevant studies have

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<sup>1</sup> ISI Web of Science search (5/15/08) on the terms "Michigan," "urban," and "nitrogen."

<sup>2</sup> ISI Web of Science search (5/15/08) on the terms "Michigan," "forest," and "nitrogen."

occurred in the states neighboring Michigan, such as Ohio and Indiana. As a result, biogeochemical research in Southeastern Michigan is distinguished from previous work by regional characteristics such as temperature and precipitation. Michigan's mean monthly temperature ranges more widely than those of many other states (-10 °C to 29 °C), while the area receives an abundance of precipitation (79 cm annually) (Carpenter & Provorse 1998). Major soil order also differs between Michigan and other states. Southern Michigan is primarily covered in Alfisols, which differentiates it from Maryland (Ultisols), New York (Inceptisols), and Arizona (Aridisols and Entisols) (National Resources Conservation Service 2008).

Due to locally distinctive temperature, geology, and precipitation factors, the biological components of the nitrogen cycle also differ between Michigan and other states. Southeastern Michigan has plant, animal, and microbial communities distinguished from those at the long-term research sites. To sum, Southeastern Michigan's particular set of nitrogen cycling factors have not yet been subject to a detailed urban-rural comparative study, with the differences sufficient to merit independent study of a biogeochemical urban-rural gradient in the region.

Southeastern Michigan's built landscape structure also differentiates this study from previous studies. Population density ranges from fewer than 40 people / km<sup>2</sup> in Saline Township to 2,647 people / km<sup>2</sup> in portions of Detroit (US Census Bureau 2008). The New York study region had a similar but narrower range of densities, ranging from 10 people / km<sup>2</sup> in Litchfield, CT to 1,000 people / km<sup>2</sup> in Westchester, NY (Pouyat 1997). Distinguishing the structure of the two regions, the NY population gradient flowed smoothly from urban to rural while the Michigan population density changes more abruptly. New

York features an urban core surrounded by irregular rings of diminishing development (McDonnell & Pickett 1990). A 20 km x 130 km belt transect originating near the city captured uniform population density across its width, as well as a linear relationship between population density and distance from the urban center. By contrast, Southeastern Michigan features a cluster of three distinct population centers (Detroit, Flint, and Ann Arbor) with severe and spatially complex population gradients between urban and rural areas. The rings of development surrounding each urban core stand in contrast to the traditional linear gradient.

The pattern of population dispersion in Southeastern Michigan suggests questions about the applicability of traditional urban-ecological effects to a new landscape paradigm. It is unclear whether many ecological impacts related to the urban halo can originate from population centers smaller than those in past urban-rural gradient studies. Similarly, it is unclear how urban-ecological effects manifest during a non-linear transition from urban to rural extremes. Southeastern Michigan features concentrated urban areas surrounded by a rapid transition to a generally low-density landscape (Liu & Rogers 2007; Southeastern Michigan Council of Governments 2008). The unique urban-rural scale and structure in the region guided the questions and methods in this study.

The precise landscape structure is partially attributable to the chosen measure of urbanization. Previous research has concentrated on measures such as governing township classification (as rural, suburban, or urban) or population density (Pouyat 1997; Pavao-Zuckerman & Coleman 2005). To integrate this study with previous and ongoing University of Michigan research on regional land-cover/land-use, the inverse of housing density (land acres / housing unit) was used as the measure of urbanization. Housing density is generally

considered a better measure of settlement area than population count (Zhao et al. 2007). Further, this metric allows for future comparisons with the widest portion of the country over the greatest time-period (Brown et al. 2005). Using this metric, questions were structured to consider fewer mean acres per housing unit as a proxy for greater urbanization.

Among the primary goals for this study was quantification of the effects of surrounding housing density on biogeochemical components within protected areas. Consequently, the working definition of protected areas excluded sites with active management, so as to avoid management actions which could potentially confound site observations. As a further control, protected areas were defined to have a relatively uniform and minimal level of recreational use.

Forests were chosen as the ecosystem study unit. As the region's unmanaged grasslands typically succeed into forests (Kimmins 1987), using mature hardwood forests guaranteed some homogeneity in site treatment and history. Further, there is a previously noted body of literature on nitrogen cycling within Michigan's forests. By focusing upon forests, soil and plant nitrogen content within research sites could be compared to reference data.

Lastly, this study is differentiated from previous studies through its integration of plant community measures at both overstory and ground-cover levels. Ecosystem accumulation of N is mediated by interactions among soil, slowly changing vegetation (overstory), and rapidly changing vegetation (ground-cover). The role of the overstory in the nitrogen cycle has been well established, with documented linkages between N storage in overstory biomass, N withdrawal from soil, and N return through decay (Finzi et al. 1998; Fisk et al. 2002; Talbot & Finzi 2008). As is common in biogeochemical research (Côté et

al. 2000; Lovett et al. 2004; Sariyildiz et al. 2005), the current study's questions include measures of overstory components. However, this study goes further and investigates ground-cover components. Ground-cover is included because its role in biogeochemical cycling is comparatively poorly understood (Small & McCarthy 2005).

Previous research has suggested several reasons for including ground-cover measures in a biogeochemistry study. Several studies have established the importance of ground-cover to nutrient retention (Guntenspergen & Levenson 1997; Compton et al. 1998; Guirado et al. 2006). Others have suggested that effective ecosystem management requires an understanding of the understory response to changing nutrient conditions (Guntenspergen & Levenson 1997; Burton et al. 2005; Duguay et al. 2007). Still others worry that the low lying community could be rapidly altered by changes in soil N (Small & McCarthy 2005). To investigate these gaps in knowledge, the research questions in the present study incorporate the biogeochemical interactions between overstory, understory, and soil. Correlation between ground-cover presence and N concentration in soil and foliage is explored.



### Questions and Hypotheses

*Q<sub>1</sub>: Does surrounding housing density affect the nitrogen concentration and C/N ratio in the soil and plants in an unmanaged forest site?*

**H<sub>1,1</sub>:** With greater housing density around a site, the soil nitrogen concentration will be proportionally greater.

Higher housing densities provide many mechanisms that could potentially drive such a difference. These include greater heat and precipitation near urban centers, with resulting higher rates of litter decomposition and N mineralization, fertilizer use by residents, and surface runoff from impervious surfaces. While these mechanisms will not be individually tested for causation, they provide plausible grounds for expecting the aggregate effect hypothesized.

(Botkin & Beveridge 1997; Pouyat 1997; Pavao-Zuckerman & Coleman 2005; Groffman et al. 2006; Pouyat et al. 2007)

**H<sub>1,2</sub>:** The stoichiometric C/N ratio in surface soil will be lower in areas with higher surrounding housing densities.

Over time, a greater accumulation of soil nitrogen through immobilization is expected than any attendant increase in soil carbon.

**H<sub>1,3</sub>:** If soils with higher surrounding housing densities are found to have increased N content relative to soils with lower surrounding housing densities, then the woody plant tissues at the higher density site will show a lower average C/N ratio.

As the nitrogen is taken in by the plant, the change in plant tissue chemistry may be the only manifestation of the increased nitrogen that was once in the soil. Plants will utilize the additional available nitrogen through luxury uptake (Schlesinger 1997).

**H<sub>1,4</sub>:** The influence of housing density will be a significant predictor of soil nitrogen chemistry, but will not be more significant than natural controls such as parent geology or wetness. Many studies have found that urban presence is a significant but secondary mechanism (Groffman et al. 2006; Pouyat et al. 2007).

*Q<sub>2</sub>: Through a decreased C:N ratio in the soil, does surrounding housing density affect plant community composition below 1m in height?*

**H<sub>2,1</sub>:** If higher N concentration is found in soil with higher surrounding housing density, then the plant community composition in urban areas will have a higher percentage of herbaceous cover. In quantifying percent cover of plants in functional groups in the ground-cover layer (< 1m height), there will be statistically significant increases in forbs and grass relative to woody plants.

Looking at an old field, previous studies found that biomass of herbaceous species increased proportionally to nitrogen addition (Tilman 1987). In a forest, assuming the amount of understory light is kept constant between sites, increased nitrogen availability should increase herbaceous biomass.

*Q<sub>3</sub>: Does surrounding housing density, through an increased N concentration in soil, affect the composition of the overstory woody plant community?*

**H<sub>3,1</sub>:** If higher N concentration is found in soil with higher surrounding housing density, lower diversity in woody plants will be observed.

Tilman (1987) found that plots receiving high rates of nitrogen addition were dominated by long-lived herbaceous species and woody species that are taller at maturity. Similarly, Groffman (2006) argued that forest community composition and soil atmosphere fluxes are more strongly influenced by exposure to urban atmospheric chemistry than by natural system controls.

In a high N availability environment, woody species will be biased towards those species that are capable of thriving in the stresses placed by the urban environment and will be dominated by a few species.

*Q<sub>4</sub>: Woody plants in urban ecosystems have been found to more rapidly accumulate biomass than equivalent plants in a rural setting (Gregg et al. 2003). Does this occur in the spatially complex urban-rural gradient of Southeastern Michigan? Is the overstory woody biomass related to nitrogen content in soil?*

**H<sub>4,1</sub>:** Urban sites will show greater woody biomass as a result of relatively higher nitrogen accumulation. Regardless of stand age, forest areas with high surrounding housing densities will have a larger total woody plant biomass as calculated through allometry. This biomass difference will correlate with higher levels of nitrogen content in soil.

**H<sub>4,2</sub>:** Plant community composition will be more highly influenced by urban controls (location relative to surrounding housing density) than natural controls (calculated soil wetness or texture) (Niemela 1999a; Groffman et al. 2006; Kaye et al. 2006).

## Methods

### Site Selection

As discussed above, the study was conducted in a subsection of Southeastern Michigan, USA (Figure 1). Within Southeastern Michigan, six counties totaling 10,522 km<sup>2</sup> (Jackson, Livingston, Macomb, Oakland, Washtenaw, and Wayne) were selected as the formal study area. This study area contains the urban centers of Detroit (population 918,849), Ann Arbor (population 114,024) and Jackson (population 36,316), as well as large expanses of medium and low density development (US Census Bureau 2008). The urban center of Flint (population 124,943) was excluded from this study. Factors contributing to the selection of the specific study area included the ability to traverse the region in a single day, the wide range of housing densities present, and the suitability of the contained protected areas.

Previous research by the non-governmental organization Ducks Unlimited produced a geographic information system (GIS) database of Conservation and Recreation Lands (CARL) in the Great Lakes States of Michigan, Indiana, Ohio, and Illinois (Wilcox & Macleod 2008). In Michigan, the CARL database contains land owned by public entities, private land protected by conservation organizations, and public and private land with conservation easements. Within the project boundaries, the CARL database designates 886 km<sup>2</sup> (8.4%) as conservation or recreation lands (Figure 2). Golf courses and athletic fields are included in this number alongside information on forests, wetlands, and other traditional conservation areas.

To calculate the housing density in the landscape surrounding a CARL area, Census 2000 block groups were imposed upon the study area (US Census Bureau 2008). With the

large extent of the project area, block group resolution offered an advantageous compromise between high detail and rapid computer processing. Additionally, block groups are the finest resolution for which the US Census Bureau publishes long form survey information. This allowed for the potential inclusion of demographic data in future analyses. Finally, census block groups have been used in several other relevant studies in the School of Natural Resources and Environment, thereby allowing cross-pollination between data resources.

Based on Taylor (2008), housing density was operationally defined as mean land acres per housing unit (LA/HU). This proxy for housing density is inverted in that a smaller value indicates a greater urban presence. Using land area, as opposed to total area, allowed for better comparison of the developed landscape in a region with widespread hydrologic resources. To calculate land area, hydrologic feature data were acquired from the Michigan Geographic Data Library (Michigan Center for Geographic Information 2008). The hydrologic features within each block group were then subtracted from that block group's total area in order to produce land area. Total housing units in each census block group were acquired from Census 2000 data. LA/HU was calculated by dividing land acres by housing units in each census block group.

Including protected areas within the "land area" metric distinguished it from a measure of developable land (Wolman et al. 2005; Taylor et al. 2007). Wolman (2005) identified a number of biases associated with the inclusion of non-developable land in a metric of urbanization, but noted the challenges inherent in identifying subjective development metrics such as topography, soil properties, hydrology, and zoning. Given that these physical and socio-political properties are not easily identified in a comprehensive manner, the simple metric of land area was used.

Based on Taylor (2008), each census block group was classified into one of four categories of housing density (Table 1). Each CARL area was assigned a mean LA/HU based on the census block group it overlaid. When a CARL area crossed into several census block groups, the CARL area was split and each portion was assigned the value of the census block group which it directly overlaid.

CARL areas, coded by LA/HU, were compiled into a list of sites that potentially contained patches of mature contiguous forest larger than one hectare (10,000 m<sup>2</sup>). Sites were selected so as to avoid “obvious” anthropogenic impacts such as management or heavy use. State and federally managed sites were removed in order to avoid potential access delays. The resulting site list contained approximately two hundred forest sites which were managed by non-governmental organizations or local governments.

Satellite photographs were used to examine the remaining sites for contiguous and mature forests with proximate road access (Google 2008). Site managers were contacted and questioned about specific management practices and usage trends at the sites.

Comprehensive landscape-altering actions such as mowing, controlled burns, or removal of vegetation disqualified a site. Large conservation areas where management activities were restricted to a region distant from the proposed research plot were allowed. Ultimately, a final list of 30 sites was produced.

From the final list, sites were visited in order to confirm the remotely sensed information and determine a set of appropriate research locations for an indirect urban-rural gradient (McDonnell et al. 1993). An indirect gradient is traditionally used when underlying factors cannot be ordinated by linear distance, but are rather grouped by ecosystem, population, or other landscape parameters. Three CARL areas were selected in each of the

housing density classes (Figure 3). Field work at these sites was conducted between June 1 and July 27, 2007.

#### Plot Design

A single 20 m x 50 m research plot was established in each site. Within the site, plots were located in edge locations in order to focus on the potential effects of the surrounding landscape. Because the experiment tested the influence of the exterior urban matrix, elevated nitrogen levels were expected to be most likely detected in the soil and vegetation at the edge of a site. If elevated nitrogen was found in these locations, future research could be designed for interior portions of the forest.

At each site, a point 10 meters from the forest's southern edge was identified. If the southern edge was inaccessible, the eastern edge was used, followed by the western. Due to its diminished relative quantity of sunlight, northern forest edge was never used. Forest was defined by a minimum standard of closed tree canopy and touching crown branches of adjacent trees. Large expanses of sky could not be visible through the forest canopy, however due to the large size of the plots and the edge location, occasional holes in the canopy were possible. Starting with the marked 10 m point, a 50 m transect was run parallel to the forest edge. This transect determined the exterior border of the research plot. From this line, the remainder of the 20 m x 50 m research plot was constructed.

A qualitative description was recorded of each site and the immediately surrounding landscape (Appendix 1). This included topography, surrounding features, location within the site, and photographs. A GPS unit was used to record the spatial coordinates of the four plot corners.

### Site Measures

In order to avoid trampling, ground-cover was sampled first. This was followed by woody plant identification, soil sample collection, and leaf tissue collection.

Based on Bonham (1989), the ground-cover was operationally defined as the percentage of ground surface covered by living plant material between the ground and a plane 1 m in height. Within the category of living plant material, the operational definition included trunks and stems of vegetation which exceeded 1 m in total height. Bare ground and ground level obstructions were also recorded. Plot design was adapted from the Modified-Whittaker plot design (Stohlgren et al. 1995). As ground-cover can be interpreted differently depending upon measurement technique (Stohlgren et al. 1998), three different methods were used for recording ground-cover. Ten 5 m x 1 cm transects were set up in the center of the plot, ten 1 m<sup>2</sup> (.5 m x 2 m) subplots were set up along the plot borders, and two 10 m<sup>2</sup> (5 m x 2 m) subplots were set in opposite plot corners (Figure 4). Within their zones, 1 m<sup>2</sup> subplots and 5 m transects were distributed through a stratified random technique. Data were collected on grass, sedge, woody plant, forbs, and obstructed cover using standard methods (Bonham 1989).

Each of the 1 m<sup>2</sup> subplots was observed using a pvc frame with border markings delineating 1% squares. A hypothetical 1 m column extending upwards from ground level in each 1% square was evaluated for presence or absence of each cover type. If a cover type existed within a 1 m x 1% column, then the area received presence credit for that cover type. This was done for each cover type in each 1% square. Cover types were collated by subplot, and rounded to the nearest 5%. The 10 m<sup>2</sup> subplots were measured by applying the 1 m<sup>2</sup> frame ten times. The 5 m x 1 cm x 1 m transects were measured using a similar technique,

but with a 1 cm horizontal resolution. Each cover was separately quantified, which resulted in an aggregate percent cover that frequently exceeded 100%.

Following Bonham (1989), specific methods were used in the calculation of each cover type. Examples include counting visible roots as woody plants and gathering grass so that only the base of each grass clump was measured. Other than grass, plants were measured as they lay, so horizontally growing plants generally counted for a greater percentage of cover than an equivalently sized vertically growing plant. Obstructions were counted only if the ground on a complete (or nearly complete) 1% square was blocked. Bare ground was recorded if no other cover type was present in a 1 m by 1% column.

Once ground-cover measures were completed, all trees in the research plot with a diameter at breast height (DBH) greater than 1 cm were identified to genus. Using genus, rather than species enabled a more rapid assessment of woody plant diversity with little loss in fidelity (Balmford et al. 1996a; Balmford et al. 1996b). Following common practice, breast height measurement of trees was recorded at 1.39 meters from the ground (Bonham 1989). Trunks that split below breast height were recorded as two separate trees.

At each site, leaf samples from approximately twenty trees were acquired. A leaf sample constituted 5-10 healthy sun leaves from a measured tree. Samples were clipped using pruning shears attached to a two meter pole. Efforts were made to ensure that leaf sample composition reflected site composition, but there were some difficulties with genera such as *Juglans* (walnut) and *Quercus* (oak) which frequently had no leaves within reach. Leaf samples were labeled by genus, site, and sample number, and then placed into individual kraft paper bags.



Four stratified soil samples were taken at each site. The plot was divided into 4 segments along the 50 m axis, and soil samples were taken at typical locations within each segment. Soil sample locations were always within 3 m of a tree trunk. Woody debris and leaf litter was cleared from the forest floor, and a 3 cm x 17 cm (width x depth) sample was removed from the ground. The sample was placed in an airtight plastic container, and labeled with site, sample number, and geographic coordinates.

#### Analysis of Field Samples

Leaf and soil samples were oven dried immediately following collection. Leaf samples were dried in a forced air oven at 67° C, while soil was dried in a gravity convection oven at 105° C. Samples were then stored in a climate controlled room for up to two months until all field work had been completed. At the mid-point of field work (July 1, 2007), all leaves were redried to 67° C. Post drying, soil samples were sieved through a 2 mm filter.

To account for the confounding effects of texture on the nitrogen content of soil (Côté et al. 2000), soil samples were analyzed for texture using standard hydrometer methods (Gee & Bauder 1986). According to the United States General Soil Map (STATSGO2), the study region varies in soil class, with portions composed of Erie-Huron Lake Plain, Southern Michigan and Northern Indiana Drift Plain, and Indiana and Ohio Till Plain (Figure 5) (National Resources Conservation Service 2008).

Soil and leaf samples were analyzed for carbon and nitrogen content by dry combustion in a Carlo Erba NC 2500 elemental analyzer attached to a Thermoquest-Finnigan mass spectrometer. To prepare the samples, leaves were ground in a Wiley mill and soil was ground in a ball mill. Ground samples were weighed and placed in tins for incineration.

Leaf and soil samples were processed in separate runs. Excluding duplicates, 241 leaf samples and 48 soil samples were analyzed.

Total foliar carbon and nitrogen at each site was calculated using C and N concentrations and allometric equations (Williams & McClenahan 1984; Boerner & Kost 1986; Harrington et al. 1989; Perala & Alban 1993; Ter-Mikaelian & Korzukhin 1997; Martin et al. 1998; Singh 1998; Chiffot et al. 2006; Jenkins et al. 2007). In order to use species specific allometric equations with genus-level data, US Forest Service Forest Inventory and Analysis Program data on stem count were acquired for the study region (USDA Forest Service 2006). The most prevalent three species of each genus were identified, as well as their relative proportions of the genus' stem count. Allometric equations were identified for each species, and the foliar biomass of each field-measured tree was calculated with each equation. A composite foliar biomass was then created for each tree by proportionally weighting the species specific foliar weights by the species' prevalence. Foliar mass was summed by genus at each site.

At each site, leaf sample carbon and nitrogen concentrations were averaged by genus. Expressed as a mass percentage, these values were multiplied by the foliar mass of that genus and summed to produce total foliar carbon and nitrogen at each site. C/N ratio was then calculated for each site. If a particular site was missing a leaf sample, the average value for that genus from all other sites was used. *Juglans*, of which there were no leaf samples, had carbon and nitrogen values calculated as an average of other members of the family *Fagales* (*Carya* + *Quercus*). For a few small shrubs with negligible biomass, leaf values were treated as the respective site's average.

Allometric whole tree biomass was calculated in a similar manner, but whole tree biomass equations were used rather than foliar biomass equations.

### Topographic Analyses

After determining precise plot location, GIS analyses were conducted on the landscape surrounding each plot. Housing density was examined at several scales, and topographic variables such as elevation, surface flow accumulation and aspect were calculated.

Housing density in the landscape surrounding each site was recalculated at several scales. In initial calculations, each CARL area had been attributed the housing density of the census block group which it overlaid (point value). If neighboring census block groups differed in housing density, sites which were located near a census block group border may not have been well represented by the point value calculation.

A more nuanced housing density was calculated after precise locations of sites were known. Using GPS plot locations, point values were compared to area weighted averages of the census blocks groups within circles of 100 m, 1,000 m, and 10,000 m radii from a plot's centroid. This analysis, conducted in STIS 1.62 (Terraseer 2008), revealed whether a site's point value was representative of the surrounding landscape. As an example, if the landscape surrounding a site contained census block groups with greater housing densities than the block group containing the site, a larger scale calculation produced a higher density. This analysis was most significant to those sites which were located near the border of a census block group. By recalculating housing density at several scales, a more representative depiction of sites was created. The reweighting still does not truly account for housing

density, as census block groups are themselves averages, but does provide a more complete picture of the variability in housing density around each site.

Using 30 m resolution digital elevation maps (DEMs) acquired from the Michigan Geographic Data Library, elevation, aspect and topographic index of wetness were calculated in ArcGIS 9.2 (Figure 6) (ESRI 2007; Michigan Center for Geographic Information 2008). Site elevation and aspect were calculated by averaging elevation values within a 100 m radius of the plot centroid. To avoid circular math issues while averaging aspect, appropriate procedures were followed (Davis 1986).

Calculating topographic index of wetness ( $w$ ) allowed relative comparison of surface runoff received by each site. Wetness was calculated as a function of upward catchment area ( $A_x$ ) and slope ( $\beta$ ) as in eq. 1 (Beven & Kirby 1979).

$$w = \log_e(A_x / \tan \beta) \quad (\text{eq. 1})$$

The wetness calculation was processed in ArcGIS 9.2. Catchment area was derived using the flow accumulation function according to the steps outlined in the program documentation (ESRI 2007). Slope was derived from the DEM and sinks were removed from the DEM before flow accumulation was processed.

#### Log<sub>e</sub> Transformation of Housing Density Proxy

The categorical classification scheme used for housing density (Table 1), which was designed to recognize distinctions in urbanization, has categories with progressively wider ranges of density. With an equivalent number of research sites in each density category, the non-linear scheme produced a research site distribution which is skewed towards the densest

end of the histogram. Consequently, a histogram of land acres per housing unit by research site indicates a left skew (Figure 7).

To normalize the distribution of sites, a  $\log_e$  transformation was used on the housing density variable (Figure 7). Three factors argued for this transformation. First, the left skew in the sites' housing density distribution does not match the assumed normal distribution for the dependent variables. Bivariate linear regression assumes equivalent distributions for all variables (assumption of linearity). Second, without transformation, the rural sites disproportionately leverage the regression. Lastly, a linear relationship between acres per housing unit and biogeochemical variables is intuitively unlikely. The change from 40 to 39 acres per unit is visually less dramatic on the landscape than the change from 2 acres per unit to 1.

A  $\log_e$  transformation of LA/HU reduces the left skew and resolves the three issues discussed above by improving the fit between the variables' distributions, reducing leverage, and producing a more intuitively plausible relationship.

As a note, trend lines show that the average (100 m, 1,000 m, 10,000 m scale) LA/HU at each site generally maintained the ordinal relationship calculated by a 100 m radius (Figure 8). This simplifies analysis, as a site presumed to be embedded in a landscape of relatively higher housing density generally maintains that ordinal position relative to other sites even as the scale of calculation increases.

### Statistical Methods

Three statistical models were used to evaluate study results. Moran's I was calculated to evaluate spatial autocorrelation of sites. Summary linear regressions were used to test statistical hypotheses, and a linear mixed model was used to compare contributing factors.

Together, the statistical models illustrate correlations between site features and the surrounding landscape.

The study sites were evaluated for a factor which was spatially affecting the entire landscape. Example factors include landscape scale gradients such as soil or elevation which affect N concentration in soil. Evidence of a whole landscape control might manifest as a combination of highly similar nearby sites and highly dissimilar distant sites (spatial autocorrelation). Most importantly, a test of spatial autocorrelation can identify whether an unaccounted factor is causing spatial similarity.

Moran's I is a commonly used measure of spatial correlation (Moran 1950; H. Kelejian & Prucha 2001). Global Moran's I measures overall spatial correlation, while local Moran's I is used to detect local spatial autocorrelation by breaking the global form into contributions from each location (AvRuskin et al. 2004). Using tests of global and local Moran's I, spatial correlation between data points can be evaluated. Tests of Moran's I were run in STIS 1.62 on mean % N in soil, C/N ratio in soil, % N in foliage, and C/N ratio in foliage (Terraseer 2008). An inverse distance weighted matrix was used.

All remaining statistical analyses were run in SPSS 15.0 (SPSS 2007). Hypotheses relating to site means were tested with summary linear regressions. In order to incorporate the internal variability in measures that were taken repeatedly at a single site (such as soil N concentration), an additional multi-tiered analysis was pursued through a linear mixed model. By using a tiered approach like a linear mixed model, estimates of standard error are improved and rates of Type I errors are decreased as compared to a summary regression (Breslow & Clayton 1993; McCulloch 2003). Akaike's Information Criterion (AIC), rather than  $R^2$ , is typically used to compare relative performance of linear mixed models (Vonesh et

al. 1996). Significant differences in linear mixed model performance were measured through chi-squared goodness of fit tests.

The linear mixed model was run with heterogeneous compound symmetry covariance. This model structure is used with data sets that have non-constant variance between a grouping variable, but constant correlation within that grouping variable (SPSS 2007). In this dataset, the model structure implies that the relationship between sites varies, but within each site the samples share the same variance structure.

When comparing models, “intercept-only” or “null model” refers to a model with no independent variables other than a constant.

#### Analysis of Vegetation Datasets

Three ground-cover datasets were produced (1 m<sup>2</sup> plots, 10 m<sup>2</sup> plots, and 5 m x 1 cm transects). This dataset structure necessitated aggregation for a comprehensive analysis of each internally heterogeneous site. For regression analysis, datasets were given equal weighting and averaged at each site. For linear mixed model analysis, individual observations were standardized so that each dataset was given equivalent weight.

Woody plant community composition was studied along size and composition axes. In terms of size, the above-ground biomass, foliar biomass, and basal area of each site were calculated through allometry. These data points, along with the number of trees, illustrate the physical size and maturity of a site.

To evaluate composition, the Shannon Diversity Index was calculated for each site. This index allows for the examination of both the species richness and relative abundance at each site. Together, the size and composition dimensions allow for a relatively complete portrayal of the woody plant composition at a site. The Shannon Diversity Index was

calculated from genus-level data. While using genus-level data has been shown to lead to an decrease in measured diversity, the relative diversity estimations can prove useful (Guerold 2000). The Shannon diversity index is normally expressed as (Morin 1999):

$$(H' = - \sum_{i=1}^S p_i \log_e p_i) \quad (\text{eq. 2})$$

Where, S is the species richness or count (or in this case, genus richness), and P<sub>i</sub> is the relative proportion of individuals of a species (or in this case genus) to the total number of individuals in the community.



## Results

### Relationship between Log<sub>e</sub> LA/HU and N concentration in Soil

Nearby sites did not possess significantly more similar soil N concentrations than distant sites (Moran's  $I = -0.16$ ,  $p = 0.16$ ). It can be concluded that factors other than a single continuous landscape-scale gradient affect the N concentration in soil. Similarly, no statistically significant clusters of sites were found with similar N concentrations in soil

Results indicate that protected areas with higher housing density in the surrounding landscape had higher soil nitrogen concentrations (Figure 9). While a summary regression showed this relationship ( $R^2 = 0.26$ ) was significant only to  $\alpha = 0.10$ , a linear mixed model showed that incorporating housing density significantly improved the model ( $p < 0.01$ ) over the null model. Relatively higher housing density in the surrounding landscape was a significant indicator of increased N concentration in soil.

The effect of housing density in the surrounding landscape upon soil nitrogen concentration may depend upon soil texture (Figure 10). Lower sand content in soil indicated a stronger relationship between housing density in the surrounding landscape and soil N concentration ( $R^2 = 0.47$ ,  $p = 0.01$ ). While the interaction of housing density and soil texture is worthy of further exploration, linear mixed models featuring an interaction term did not perform significantly better than models featuring housing density alone ( $\chi^2$  goodness of fit test,  $p = 0.15$ ).

### Stoichiometric C/N Ratio in Soil

The study region possessed a mean soil C/N ratio (by mass) of 13.43 with a standard deviation of 1.59. Only one of the 48 soil samples had a C/N ratio which exceeded 18 (Figure 11). Housing density in the surrounding landscape was not a significant control of stoichiometric C/N ratio in forest soil (Table 4).

While model performance was best at the 1,000 m scale, model results for both N concentration and stoichiometric C/N ratio in soil indicated there was little difference in model performance when density was calculated at either the 100 m or 1,000 m scale (Table 4). Consequently, all further analyses were conducted at the 1,000 m scale.

#### Foliar Nitrogen Concentration and C/N ratio

The housing density in the surrounding landscape did not have a significant effect on foliar nitrogen content in Southeastern Michigan protected areas. There was little relationship between  $\log_e$  LA/HU and foliar nitrogen concentration ( $R^2 = 0.11$   $p = 0.30$ ) or C/N ratio ( $R^2 = 0.06$ ,  $p = 0.46$ ). Similarly, the relationship between soil nitrogen concentration and foliar C/N ratio was insignificant (Table 5).

#### Comparison between Housing Density and Geologic/Topographic Controls

While higher housing density in the surrounding landscape generally indicated higher mean soil nitrogen concentration in a protected area, geologic and topographic (GT) factors were generally better predictors of the same (Table 6, Figure 12). As an example, sites at higher elevations generally had lower soil mean nitrogen concentrations ( $R^2 = 0.52$ ,  $p < 0.01$ ), and elevated sites with high sand content tended to have the lowest mean nitrogen concentrations ( $R^2 = 0.82$ ,  $p < 0.01$ ). Elevation derived variables such as aspect and topographic index of wetness were also significant predictors of mean soil nitrogen concentrations in a protected area, with wetter sites likely to have higher mean nitrogen concentrations in soil.

While the GT variables were generally better predictors of mean site nitrogen concentration, housing density and GT based models performed equally well when

considering all soil samples at a site (AIC of 137 vs. 140, Table 6). When internal site variability is considered, GT variables and housing density are roughly equivalent predictors.

The landscape structure did not control soil C/N ratios, as soil C/N ratios were uncorrelated to GT variables (Table 6). Housing density and GT variables were equally poor predictors of soil C/N ratio.

#### Surrounding Housing Density and Ground-cover

In Southeastern Michigan protected areas with controlled management and use, the surrounding housing density did not have a significant effect on ground-cover (Table 7). This statement is limited to the ground-cover categories of woody plants, forbs, and bare ground, as little grass or sedge was encountered during fieldwork. No significant relationships were found between ground-cover and soil N concentration.

Regardless of soil nitrogen concentration or C/N ratio, results showed that overstory biomass was a strong control on ground-cover composition (Figure 13). While not included in the hypotheses, an increase in site overstory biomass correlated with an increase in bare ground ( $R^2 = 0.67$ ,  $p < 0.01$ ) and a decrease in woody plant ground-cover ( $R^2 = 0.37$ ,  $p = .04$ ).

#### Housing Density and Overstory Woody Plant Composition

Sites varied in overstory woody plant characteristics such as stem count, basal area and biomass (Figure 14). The majority of sites (7) possessed stem counts of 150 to 200 trees. When the site with the fewest stems and lowest biomass is excluded, protected areas surrounded by lower density housing have predictably lower total overstory biomass ( $R^2 = 0.60$ ,  $p < 0.01$ ) and basal area ( $R^2 = 0.44$ ,  $p = 0.03$ ). .

Contrary to the mechanism proposed in the hypotheses, nitrogen concentration in soil may not be the driver behind the relatively higher overstory biomass at urban sites. While nitrogen concentration in the soil was found to be higher at sites with greater housing density in the surrounding landscape, the relationship between biomass and soil nitrogen concentration is statistically insignificant ( $R^2 = 0.02$ ,  $p = 0.72$ ).

In terms of composition, 2,027 trees were identified across the study region. The trees possessed a mean dbh of 9.82 cm and a standard deviation of 12.22 cm (Figure 15). While 24 total genera were encountered, the three genera *Acer*, *Carya* and *Quercus* accounted for 83.7% of total biomass and 74.1% of total basal area. Stem count was dominated by *Prunus*, *Quercus*, *Ostrya*, and *Acer*, which accounted for 67.3% of total trees. In eleven genera, less than 25 stems (1% of total) were encountered. *Rhamnus* and *Robinea* featured the highest foliar nitrogen content (Table 8).

Surrounding housing density does not significantly affect site woody plant diversity through an increased N concentration in soil. The mean Shannon index (calculated by genus) for the twelve sites was 1.52, with a standard deviation of 0.44 (Figure 16). Correlation between Shannon index and N concentration in soil was poor ( $R = 0.06$ ,  $p = 0.86$ ), as was the correlation between Shannon index and  $\log_e LA/HU$  ( $R = 0.24$ ,  $p = 0.45$ ).

In this subset of protected areas, diversity appeared to be controlled by tree count and foliar chemistry. Shannon index was best predicted by a regression model including the variables: number of trees, foliar N concentration, foliar C concentration, and foliar C/N ratio (Adjusted  $R^2 = 0.56$ ,  $p = 0.04$ ). Given that foliar chemistry and number of trees are statistically uncorrelated with housing density, housing density in the surrounding landscape has little effect on Shannon index.

## **Discussion**

### Nitrogen Content in Forest Soil and Housing Density in the Surrounding Landscape

As seen above, a statistically significant positive correlation was found between soil N concentration in protected areas and the housing density in the surrounding landscape.

Current study results showing predictably altered soil N concentrations along an urban-rural gradient are consistent with previous research corresponding urban land-cover with increased N mineralization in Arizona, Maryland, New York, and North Carolina (Pouyat 1997; Zhu & Carreiro 2004; Hope et al. 2005; Pavao-Zuckerman & Coleman 2005; Szlavecz et al. 2006).

While the present study did not measure N mineralization, increased N concentrations are consistent with increased N mineralization (Aber et al. 1995), especially in the presence of low forest soil C/N ratios (Gundersen et al. 1998a; Gundersen et al. 1998b). Current study results, which were based upon census block group housing densities, support the impact of landscape-level anthropogenic controls on soil nitrogen content within protected areas.

Current study results question arguments that surrounding urban land-use has an unpredictable effect on forest soil N dynamics (Groffman et al. 2006). While supporting the role of geologic and topographic factors as an important determinant of N dynamics, current study results reinforce the correlation between urban presence in the surrounding landscape and increased soil N content. A consistent but weak empirical association is consistently found between surrounding urban land-cover and predictably altered N dynamics.

### Comparison between Housing Density and Geologic/Topographic Controls

While the current study found a relationship between housing density and soil nitrogen concentration, results indicated a general preference for geologic and topographic (GT) variables when predicting soil nitrogen concentration. GT factors generally explained a greater portion of the data than housing density alone. Incorporating both GT and

urbanization factors (such as  $\log_e \text{LA/HU} \times \% \text{ sand}$ ) anecdotally improved predictive abilities, but did not produce a statistically significant improvement.

The general preference for GT models is consistent with other research in the field (Groffman et al. 2006; Pouyat et al. 2007). As a proxy for ecosystem process, GT controls were generally simpler to understand and correlated more directly with mechanistic explanations. For example, the flow of nitrogen-filled runoff is a mechanistic hypothesis for the correlation between elevation and N concentration in soil. By contrast, housing density-based variables were generally more complex surrogates for a host of factors. The urban heat island, surrounding impervious surfaces, fertilizer use, agricultural abandonment, biogeochemical hotspots and other urban correlates are all wrapped into a single proxy variable. The aggregate approach is an interesting phenomenon, but is mechanistically unclear.

Current study results indicated significant correlations between housing density in the surrounding landscape and ecosystem responses (increased N concentration in soil and increased overstory biomass) and beg questions about the particular component of surrounding urban land-cover that drives the response. Future research should investigate whether the same mechanism operates at every site, or whether the conglomeration of different mechanisms tends to act in certain fashion. The McDonnell (1993) framework is useful for future disaggregation of these variables. Breaking subtle urban biogeochemical effects into the mechanistic categories of “indirect effects,” “historical effects,” “lagged effects,” or “unexpected actions at a distance” may provide further insight. A single of these framework effects may be dominant.

### Nitrogen Availability in the Study Region

While a large number of sites (12) were sampled in the current study, soil stoichiometric C/N ratios were uniformly low. As previously stated, mean soil C/N ratio for the study region was 13.43 with a standard deviation of 1.53 (Figure 11). The recorded range of values was narrow with no sample C/N ratio above 19 or below 11. Soil C/N ratios at this low level are potentially problematic, as they frequently indicate nitrate leaching (Gundersen et al. 1998b). While direct comparison between studies is hampered by differences in soil horizons sampled and sampling technique, Gundersen (1998b) argued that nitrogen saturation begins when forest floor C/N ratio is below 25. Correspondingly, it can be inferred that forest soil in Southeastern Michigan is highly N-rich relative to carbon content.

Current study results are consistent with results from Michigan and other areas of the northeastern United States. As a reminder, current study soil sampling technique excluded the high C/N ratio leaf litter layer, and combined O<sub>e</sub>, O<sub>a</sub> and upper mineral soil to a depth of 17 cm. By comparison, in O<sub>e</sub> horizon samples, a mean soil C/N ratio of 20.6 was found in Northern Lower Michigan forests (Zak & Pregitzer 1990). Similarly, in the White Mountain Region of New Hampshire, a mean C/N ratio of 18.5 was found in the upper mineral soil (Bohlen et al. 2001). A third set of results from a Northern Connecticut forest possessed a mean C/N ratio of 17.1 (sample from forest floor to 15 cm in depth) (Finzi et al. 1998). While Southeastern Michigan forest soil appears to be quite nitrogen-rich, the differences in soil C/N ratio can be partially explained by differences in sampling methodologies between studies. In summation, the mean soil C/N ratio of 13.43 found in the present study is low but plausible in the context of northeastern forests.

In terms of study results, consistently low soil C/N ratios may partially obscure the hypothesized soil differences between urban and rural areas. Additional biogeochemical

distinctions driven by the landscape may be hidden by the uniformly nitrogen-rich soil. As a second concern, with a set of already nitrogen-rich study sites, limited retention of nitrogen inputs from the surrounding landscape to the protected area is expected (De Schrijver et al. 2008). Once the soil C/N ratio drops beneath a critical point, nitrification tends to increase, thereby making N mobile and more easily lost from the system (Currie 1999). While a certain housing density may correlate with greater N inputs to a protected area, the inputs may not accumulate within the already N-rich soil at the site.

Regionally low soil C/N ratios are a challenge for both terrestrial and aquatic management. As discussed in the introduction, high nitrogen availability has implications for terrestrial community composition. N availability is a partial determinant of the growth rate of individual vegetative species (Olde Venterink et al. 2001; Henry et al. 2005; Kobe 2006), and their ability to effectively compete (Lowe et al. 2003; Hangs et al. 2004). Consequently, the currently N-loaded forest systems in Southeastern Michigan may be altering in composition relative to the previously N-deficient systems. Changes in relative prominence of species, and incursion of new species are both possibilities (Huenneke et al. 1990; Stohlgren et al. 1999), as is degradation of the native communities (Mack et al. 2000). Over extended periods of time, N leaching and runoff can affect regional water supplies by stripping nutrients from forest soils, acidifying water sources and altering aquatic community composition (Lovett et al. 2002). Hypoxic and eutrophic regions, which may eventually result from high quantities of additional aquatic nutrients, are an issue of long-term concern.

Immediate management options to mitigate low C/N ratios in forest soils are not obvious. With the wide extent of nitrogen-rich soils and relatively low levels of carbon and organic matter in the soil, few direct actions are available. As a first step, additional linkages



between regional sources of nitrogen and forest soils must be identified. While this study examined intra-region differences in nitrogen concentration, there are also larger scale factors affecting Southeastern Michigan. As an example, Southeastern Michigan receives among the highest rates of inorganic nitrogen deposition in the country ( $> 7$  kg/ha), with recent trends indicating that these rates are level or increasing through time (National Atmospheric Deposition Program 2008). Excessive use of agricultural fertilizer is also a potential source of free reactive N. While the region has rapidly converted agricultural land to residential use, significant agricultural lands remain (Brown 2003). A comprehensive state-wide assessment of hydrologic nutrient movement is a potential direction for future research. While catchment-scale research has been conducted (Bosch & Allan 2008), a larger scale understanding of nitrogen sources and movement within the state will enable better management of soil nutrient properties.

#### The Effects of Time and Agricultural Abandonment

Historical effects sensu McDonnell and Pickett (1993) may contribute to regionally low forest soil C/N ratios, as well as partially explain the relationship between housing density in the surrounding landscape and soil N concentration. Agricultural use, which was historically prevalent in the region (Brown 2003), typically corresponds with a long term diminishment of soil carbon content (Knops & Tilman 2000). With carbon content a major factor contributing to nitrogen retention in soil (Currie 1999), date of agricultural abandonment thus influences soil nitrogen content and C/N ratio.

Present day forests in Southeastern Michigan were frequently grown on previous agricultural fields (Brown 2003; Botti & Moore 2006), and are a product of that agricultural legacy. Relevant to study results, an agricultural field at the time of abandonment generally

has drastically reduced carbon relative to control fields. As an example, a Minnesota sand plains study showed that an average abandoned agricultural field has 89% less carbon at the time of abandonment than an uncultivated control field (Knops & Tilman 2000). The carbon depletion effects are long lasting, with a typical 50-year abandoned agricultural field possessing highly reduced ( $\approx 30\%$ ) carbon content in soil as compared to uncultivated areas (Kalisz 1986; Compton et al. 1998). While the timing is dependent on vegetation, soils and climate, near complete recovery of carbon is predicted to take several hundred years (Knops & Tilman 2000).

The documented relationship between soil carbon and agricultural history, along with present study results indicating a strong correlation between soil carbon and nitrogen ( $R = 0.94$ ,  $p < 0.01$ ), suggest that protected areas with higher housing density in the surrounding landscape may have gone through an earlier process of agricultural abandonment. Supporting the idea of systemic differences in date of agricultural abandonment, Wisconsin data from the years 1938 - 1992 demonstrated a high correlation between population density and conversion from crop land to grassland (Burgi & Turner 2002). A similar Massachusetts study indicated that the smaller agricultural plots near town centers were generally abandoned earlier than larger rural farms (Foster 1992). While geophysical characteristics play a part (Foster et al. 1998), farm sites near urban centers in both New England and the Midwest frequently went through an earlier process of agricultural abandonment.

Regional forest soil C/N ratios may be similarly driven by an interaction between previous agricultural intensity and stand age. In areas with agricultural histories similar to Southeastern Michigan, stand age (as a surrogate for time since agricultural abandonment) has been shown to positively correlate with increased soil C/N ratios (Compton et al. 1998).

Date of agricultural abandonment would also presumably affect the quantity of overstory biomass, which was the other significant correlate with housing density. The relationship between overstory biomass and date of agricultural abandonment is intuitively due to the positive relationship between total stand biomass and stand age (Le Toan et al. 1992). However, as a second contributor, old field biomass is highly correlated to N-pool size (Zak et al. 1990). As discussed, N pool sizes are dependent upon soil carbon pools, which are in turn dependent upon temporal distance from agricultural abandonment. Soil carbon, soil nitrogen and plant biomass can thus form a positive feedback loop whose intensity increases through time (Aber et al. 1998).

Returning to the questions posed in this study, it is unclear whether urban sites receive higher external inputs of N from the surrounding landscape as compared to rural sites, or whether they are simply older forests. This analysis requires further exploration to disentangle site history and landscape-level factors. When considering mechanism, date of agricultural abandonment may be considered as a parallel hypothesis to the nitrogen mobility hypotheses discussed in the introduction.

#### Nitrogen Content in Woody Plant Foliar Chemistry

As discussed in the introduction, foliar nitrogen content is used as an indicator for many processes. There are positive correlations between foliar nitrogen and N deposition rates (McNeil et al. 2007), maximum photosynthetic rates (Kobe 2006) and carbon uptake (Elvir et al. 2006).

Chemical analysis of present study leaf samples suggests that foliar nitrogen concentrations are relatively high in the region (Table 8). Averaged by site, mean nitrogen concentration across all overstory foliage is 2.14%. Averaged by sample, mean foliar N

concentration in the prevalent genera of maple (*Acer*) and oak (*Quercus*) were respectively 1.94% and 2.16%. While comparing foliar chemistry across sites is challenging, a number of regional foliar surveys provide the opportunity. A New Hampshire study of a diverse set of nitrogen-rich hardwood plots reported a range of mean foliar nitrogen concentrations from 1.61% to 2.36% (Ollinger et al. 2002). Research on high fertility Northern Michigan hardwood sites reported red oak (*Quercus rubra*) samples with a mean N concentration of 2.84% and red maple (*Acer rubrum*) samples with a mean N concentration of 1.88% (Kobe 2006). A third study in the nitrogen-rich Adirondack Mountains (New York) found mean foliar N concentrations that ranged from 2.50% to 2.96% in hardwoods, with Red Maple foliar N concentration at 2.50% (McNeil et al. 2007). Mean foliar nitrogen concentrations in the current study were similar to these other N-rich sites, indicating overall high levels of nitrogen in the Southeastern Michigan forest overstory.

While the present study found poor correlation between foliar and soil nitrogen content (Table 5), the high N concentration in foliage indicated that the regionally high soil N concentration affected the woody plants. The uniformly high nitrogen concentrations in soil and vegetation may present insufficient variation for a complete analysis of correlation between the two. Alternatively, the poor correlation between foliar and soil nutrient concentrations can potentially be attributed to a number of factors, including the heterogeneous woody plant communities between sites (Tanner et al. 1998). The movement of soil-based N to foliage is known to differ by species and stand age (Magill et al. 2004; Bond-Lamberty et al. 2006), with changes in foliar chemistry tending to lag behind changes in soil chemistry (Aber et al. 1995; Bowman et al. 2003; Magill et al. 2004). The

insignificant correlation between foliar and soil nitrogen may be an artifact of aggregate lags in N uptake that differ between sites.

The high nitrogen availability to woody plants has implications for regional carbon storage. Woody plant biomass accumulation has been positively correlated with nitrogen availability (Magill et al. 2004), with foliar nitrogen content a leading indicator of maximum photosynthetic rate (Kobe 2006). The high carbon storage potential of Southeastern Michigan is worthy of further exploration.

#### Surrounding Housing Density and Ground-cover

Previous research has established the role of canopy closure in determining understory composition in forests and woodlands (Zavitkovski 1976; Pieper 1990). On a related note, canopy closure has been shown to correlate with overstory basal area (Alaback 1982; Lewis 1989), which is in turn proportional to overstory biomass (Chiba 1998). Building on these findings, present study results indicate that overstory biomass was more influential than soil nitrogen content in determining ground-cover establishment and growth in Southeastern Michigan forests (Figure 13). This relationship may be attributable to the correlation between overstory biomass and canopy closure.

The use of overstory biomass, which is often remotely sensed (Van Tuyl et al. 2005; Broadbent et al. 2008), as an estimator of ground-cover offers potential future benefits. Ground-cover is known to affect soil nutrient retention, erosion, and other important factors (Nearing et al. 2005; Olde Venterink et al. 2006). The use of biomass as a remotely sensed proxy for ground-cover may offer low-cost methods for large-scale, low-resolution vegetation surveys.

The strong relationship found between overstory biomass and ground-cover may be partially attributable to regionally high nitrogen availability. With nitrogen-rich soil, alternative resource limitations may have greater effect. Further investigation into the relationship between nitrogen, biomass, and ground-cover is warranted in an area with a wider range of soil nitrogen content than that of the current study. Additionally, while present study plots were exclusively placed under closed canopy, future research should include explicit canopy measures such as overstory leaf area, canopy closure and light penetration. Controlling for these variables in future studies could provide additional insight into the relationship between overstory biomass, forest ground-cover and soil nitrogen content.

#### Overstory Composition

In a temperate forest, Shannon index typically ranges from 1.5 to 3, with higher values indicating a more even distribution of individuals among species (Singh 2005). The current study data exhibit lower values which are consistent with genera-level usage of the Shannon index (mean of 1.52) (Guerold 2000), and which are consistent with the genus composition of the oak-savanna and oak-hickory communities prevalent in the region (Barnes & Wagner 2003). The Poisson distribution of the index values between urban and rural sites is notable, as it implies that the study sites at each end of the urban-rural spectrum have similar diversity among woody plants. Present study control of disturbance, normally an urban correlate that affects diversity (Blair 1996; Blair & Launer 1997; Burton et al. 2005), is supported by this Poisson distribution.

As with other measures, interpretation of overstory composition data may be biased due to the region's high nitrogen availability. All sites in this study may be undergoing

biogeochemically driven composition changes, but without any N-poor local sites, no comparative composition controls are available. Plant species with low N tolerance may have already been completely extirpated from the region.

#### Conclusions: Indirect Urban Gradients, Non-Linear Relationships and Scale

Study results indicate that the fragmented urban landscape of Southeastern Michigan demonstrated a parallel increase between nitrogen concentration in forest soil and housing density in the surrounding landscape. This correlation is similar to the correlation between urban land cover and increased N mineralization found in the linear urban-rural gradients in New York, Maryland and Arizona (Pouyat 1997; Zhu & Carreiro 2004; Hope et al. 2005; Szlavecz et al. 2006). While confounding factors have enabled criticism of these previous studies (Groffman et al. 2006), the current study highlights a pattern of predictably increased nitrogen content in protected areas with greater surrounding urban presence. An increase in overstory biomass proportional to the  $\log_e$  LA/HU of the urban areas, not noted by other studies, was also found.

Southeastern Michigan is a nitrogen-rich landscape, with low C/N ratios and high nitrogen concentrations in both soil and foliage. In a region with such high nitrogen availability, forest ground-cover was proportional to overstory biomass, and likely controlled by canopy closure rather than nitrogen limitations. The nitrogen-rich soil also poses long-term concerns for terrestrial and aquatic ecosystem management.

Questions of scale remain. Spatially, the current study demonstrates that an indirect gradient sensu McDonnell and Pickett (1993) is an appropriate tool for the study of biogeochemistry along an urban-rural spectrum. Housing density at the census block group scale was found to be relevant to an ecosystem, both in terms of soil nitrogen content and

overstory biomass. Urban effects were thus found to be correlated to the local surroundings, rather than simply correlating to distance from an urban core as in a linear belt transect. In terms of the relationship between housing density and related changes in the environment, the non-linear ( $\log_e$ ) relationship between LA/HU and biogeochemical properties suggests that the first few housing units in an area are the most impactful, but it is unclear whether this is a universal relationship or attributable to some unique feature of the Southeastern Michigan landscape. This tension between local population centers and large scale urban effects will require further investigation as the population of the United States continues to deconcentrate across the landscape.



## Appendix: Site Descriptions

**Visited:** 6/1/2007  
**Name:** Edwin S. George Reserve  
**City:** Putnam.  
**Class:** Urban  
**Contact:** Earl Werner, Director

### Official Description:

“Since 1930, the University of Michigan has maintained the Edwin S. George Reserve (ESG) for the purposes of providing research and education opportunities in the natural sciences and preserving the native flora and fauna. The ESGR is a 525-hectare fenced preserve located in Livingston County, Michigan (about 25 km Northwest of Ann Arbor), which was presented to the University as a gift by Edwin S. George in 1930. The ESGR is characterized by a rugged moraine and basin topography supporting a rich fauna and flora. The ESGR is administered by the Department of Ecology and Evolutionary Biology at the University of Michigan.”

### Notes:

The ESG is gated, open only to researchers, and the vegetation is not managed. It features numerous wet areas, as well as significant forests and fields. The site at the ESG was located off the main road, near the map section labeled E-15, South Woods. It was located at the top of a hill, about a 5 minute hike off Crane Pond road. The forest looked like an early successional forest, primarily composed of cherry, hickory, and oak. Likely, the tree line was advancing over the old field that was to the south. This plot was slightly farther from the border of the reserve than our typical site (almost 50 meters), but started at 12 meters from the closure of the canopy on the south side.

Site was at the top of a hill, and fell off quickly on the north and west sides. Area farther north was heavily dominated by grass, whereas there was little in our plot. 4 square meters in the plot were taken by an abandoned collection pit from the mid-1990's. We were told by Director Earl Werner and former Director Ron Nussbaum that it was likely left from Burt Barnes' oak collection project, and that it was “highly unlikely” that any chemical had been added to the environment. Ground-cover here was moderate, with a high percentage of forbs.

**Visited:** 6/6/2007  
**Name:** Black Pond Woods  
**City:** Ann Arbor  
**Class:** Suburban  
**Contact:** Lara Treemore-Spears, Department of Natural Area Protection

### Official description:

“Black Pond Woods (BPW) is a 34-acre woodland on the north side of the city off Traver Rd. It is bordered by Leslie Golf Course on its east side, and it is located north of the Leslie Science Center. Parking is available in the Leslie Science Center parking lot. No facilities are available in this undeveloped park. The trails wind through the woods of oak,

hickory, maple and dogwood. The spring wildflowers offer a terrific show. Black pond is a vernal or seasonal pond, and its murky waters support a variety of wildlife both terrestrial and aquatic.”

Notes:

BPW is a heavily trafficked park, with constant dog-walkers and joggers on the trails. Vegetation in the southernmost portions is fairly scrubby. To reach a site with suitable canopy, we traveled to the east side, and oriented the plot with 50m traveling north/south. The plot was located just south of the water featured in the northeastern quadrant. The eastern canopy line bordered the golf course. There were significant topographic changes over the course the plot, with the southern side highly elevated relative to the center, and the northern side at a mid height. The plot fell off to the east.

North of BPW, Leslie park is located, and south of BPW, the Leslie Science Center is located. West, houses are found. Management in BPW is inconsistent. In certain areas near the south side, fire has been used to reduce the quantity of scrub and garlic mustard. Garlic mustard pulls have also taken place. We saw little evidence of management activity in the area in which we worked. We noted four stumps, which were likely buckthorn, that had been cut several years prior. Otherwise, management was minimal in the remote, near the golf course area. This location had the most undergrowth of any area in which we worked.

**Visited:** 6/13/2007  
**Name:** Pittsfield Preserve  
**City:** Pittsfield  
**Class:** Exurban  
**Contact:** Dan Cooperider, Director of Parks and Recreation

Official description:

“In late April, 2002, Pittsfield Charter Township completed the purchase of 535 acres of new parkland, located north of Michigan Ave., and bounded by Morgan, Marton, and Platt Road. This township acquisition, historic in both its size and richness of natural features, straddles two watersheds--the Huron River, and the Saline River, a tributary of the River Raisin. The park holds a Great Blue Heron colony of over 40 nests, a buttonbush swamp harboring threatened species, and numerous small wetlands, woods and meadows. The new parkland surrounds the township's previously acquired P.G. Palmer Park, 39 acres of woodland, wetlands, and open field, and the Morgan Road pump station, on 20 acres of mature woods. The Park Commission is working to create a master plan for the new park, incorporating trails and nature observation, and facilities for active recreation.”

Notes:

We worked in the eastern area bordering US-12. This area is likely wet for a portion of the year. Area was flat, heavily mosquitoed, and full of ground-cover. Virginia creeper was a heavy presence. We parked on US-12, and moved 10m into the woods.

No management has taken place since the 2002 purchase, and based on the looks of the area, it is unlikely that significant management activities took place in the time immediately preceding. There were no paths, and no visitors were seen. While the area is open to the public, the lack of trails and parking, along with the mosquitoes, likely

discourage most prospective attendees. Because of the proximity to the road, access was really easy.

**Visited:** 6/18/2007  
**Name:** Valley Woods  
**City:** Southfield  
**Class:** Urban  
**Contact:** Merrie Carlock, Park Planner

Official Description

None

Notes:

Valley Woods Nature Preserve is split in half (east/west) by a river and thirds (north/south) by roads. It has been a city park since 1972. After more than an hour of exploring the riverbanks, we were unable to find a suitable site on the east side of the river, where the primary paths are located. We noticed suitable woods on the west bank, and after parking in an architect's parking lot, we explored the area behind several of the businesses. We found one of the few areas with sufficient cover behind an abandoned building, in an area that was littered with trash from the dumpsters that were located directly west and above the site. A 18m by 2m strip of the plot was bare due to some kind of spilled waste (possibly antifreeze or salt). We entered the site by trespassing across the abandoned building, and then descended into the site. The site descended relatively sharply to the east. As a result of site conditions, we were within 10m of the western canopy opening, and received additional light from the north and south. We were less than 60m from a road, and 10-15m from private property.

Given those caveats, there was little active management in our portion of the park. Merrie Carlock indicated that there had been buckthorn and garlic mustard removal in Valley Woods. Given that we saw areas covered with mature stands of each, it is unlikely that any management activities had taken place in this area. Because of its topography/isolation, many large trees were located in the area. We saw deer, and encountered few mosquitoes. We were not located near paths, and while we saw evidence of human activity (trash), we did not see any other people near our site.

**Visited:** 6/22/2007  
**Name:** Lefurge Woods Preserve  
**City:** Superior  
**Class:** Rural  
**Contact:** Scott Tyrell, Stewardship Coordinator, Southeastern Michigan Land Conservancy.

Official Description:

“Over the course of 12 years, the Conservancy made five land purchases to consolidate 325 acres of farm land and natural habitat along Prospect Road in Superior Township. LeFurge Woods Nature Preserve now protects a wonderful cross section of southern Michigan habitat types. Trails wind throughout wetlands, meadows, agricultural

lands, and, of course, wonderfully preserved LeFurge Woods to allow visitors some of the best wildlife viewing in the Detroit-Ann Arbor region.”

Notes:

Lefurge featured the most difficult access of any forest region in which we worked. We needed to acquire a gate key, and then in order to reach a southern edge, we hiked more than 20 minutes through a field and then the woods. The woods feature no paths. We saw no visitors. The southern border ended in a meadow, while the nearby western border terminated in a farmer’s field.

The terrain was flat, and the area was relatively high quality. Virginia creeper was present in quantity. Invasive species removal had taken place in the northern area of the preserve, but none had taken place in the southwestern corner in which we worked. Scot Tyrell attributed the low levels of ground-cover and leaf litter to an extremely high presence of worms.

**Visited:** 6/28/2007  
**Name:** Osborne Mill Preserve  
**City:** Ann Arbor/Scio  
**Class:** Exurban  
**Contact:** Faye Stoner, Parks Naturalist, Washtenaw County Parks

Official Description:

“A simple road junction marks the edge of a hidden gem among County Park properties, one with an unusually rich natural history. The 39-acre Osborne Mill Preserve lies along an oxbow of the Huron River just south of Delhi Metropark. Osborne Mill’s unassuming entrance is located on East Delhi Road just south of the West Delhi Road junction.

“Parks Naturalist Catherine Marquardt recently conducted a detailed assessment of plant and animal communities at Osborne (see “Natural Features Inventories”, Winter 2004-2005). Her work revealed a rich interaction of ecosystems, comprising both dry upland and wet floodplain habitats of forest, prairie, and meadow. The drier soils of the uplands contain plant communities that are distinct from the moisture-tolerant species of the lower floodplain zone. The upland forest contains taller “overstory” trees layered above smaller “understory” trees and shrubs. The overstory species include Shagbark hickory (*Carya ovata*), Shingle oak (*Quercus imbricaria*), and the unusual Chinkapin oak (*Quercus muehlenbergii*); the understory layer includes Flowering dogwood (*Cornus Florida*) and Downy serviceberry (*Amelanchier arborea*). All of these tree species exhibit wonderful fall colors, and the oak acorns, hickory nuts, and serviceberries provide food for wildlife. Many broad-leaved herbaceous plants (or forbs) are found in areas where the understory is less dense, such as Twinleaf (*Jeffersonia diphylla*), a Michigan Species of Special Concern. The northern tip of Osborne is a remnant of tallgrass prairie habitat containing native species such as Big bluestem (*Andropogon gerardii*) and an abundance of Goldenrods (*Solidago* spp.). The southeast end is a wet meadow dominated by sedges (*Carex* spp.), Joe-pye weed (*Eupatorium maculatum*), Marsh fern (*Thelypteris palustris*), and Marsh bellflower (*Campanula aparinoides*). Along the river to the south is a small stand of floodplain forest containing

Black willow (*Salix nigra*), Red ash (*Fraxinus pennsylvanica*), and even Honeylocust (*Gleditsia triacanthos*)—a species that is now relatively uncommon for this area.”

Notes:

We worked just west of the water way, in the thin strip of upland forest bordering the floodplain forest. In general, Osborne Mill is a relatively low quality forest that is filled with buckthorn, and it was difficult to find an area with sufficient overstory. On the southcentral edge, we found a site that was acceptable, although it was nearer to trails than typical. South of Osborne Mill is additional forest. The Huron river is to the east, and delhi metropark is north. To the west and southwest, housing can be found. Hike was approximately 12 minutes.

Osborne mill’s maintenance is under Ann Arbor parks, but no restoration work has taken place in the wooded areas in the park. Main trails have been mowed, but side trails are dirt and unmarked. Other than a slight gully, the terrain was relatively flat. This was the first date when we saw herbaceous material starting to die, but it was only a small segment in a limited area and might be attributed to local conditions. We saw 2 people over the 16 hours at the site.

**Visited:** 7/1/2007  
**Name:** Saginaw Forest  
**City:** Scio  
**Class:** Suburban  
**Contact:** Debra LeFree, University of Michigan School of Natural Resources.

Official Description:

“Saginaw Forest is an 80-acre parcel of land surrounding Third Sister Lake. Access is from Liberty Road, which constitutes the south boundary of the property. The site is most distinctive because the origin of the School of Natural Resources and Environment (SNRE) is integrally tied to Saginaw Forest, which was purchased in 1903 for forestry operations, research, and instruction. Forest planting by the first students and faculty of the School commenced when the parcel was purchased in 1903-04, the first year of SNRE's existence. Planting continued up until 1937, resulting in a total of 47 acres of forest plantings of several tree species, both native and exotic.”

Notes:

We used a portion of Saginaw Forest that was to the Southeastern edge, bordering West Liberty Street. Our area was more than 200 meters from the main trail and entrance. Cutting or collecting of plant material is forbidden by visitors. Garlic mustard was prevalent. Area was exceedingly flat, and this was the first site that we were able to complete in two, as opposed to three, days. Cherry trees were prevalent. We could hear visitors at the site, frequently with pets, but could not see them as we were far from the trails. Conversations with the caretaker confirmed that there was no management of woody species, and minimal management of herbaceous species (1 day of volunteer pulling more than a year previous).

**Visited:** 7/11/20007  
**Name:** Nan Weston Preserve  
**City:** Sharon Hollow  
**Class:** Rural  
**Contact:** Patrick Doran, The Nature Conservancy

Official Description:

“The variety of wetland plant communities at Nan Weston Nature Preserve at Sharon Hollow reflects the amazing underlying geological diversity—from streams lined with silver maple, red ash and swamp white oak to swampy areas filled with black ash, American elm and yellow birch. Sandhill crane, chestnut-sided warbler, barred owl and dickcissel are a sampling of the birds you might see. The Nature Conservancy allows bow hunting for white-tail deer on this preserve to reduce an unnaturally high deer population in the area and reduce threats too many deer pose to our conservation targets.”

“Spring peepers create an impressive display starting in late April, when the male frogs vocalize in an attempt to find a mate in the vernal breeding ponds. A vast variety of wildflowers carpet the different habitats starting in early May and flourishing throughout the summer. Migratory songbirds are also present in both the spring and fall. In the spring, be prepared for wet, muddy trails by wearing waterproof boots.”

Notes:

Nan Weston is a 249 acre park. We worked just inside the park boundary, with a road to the north, a field to the east, trails on the western border. We saw a single visitor during the two day experience. The northeastern corner of the plot was on a downslope relative to the rest of the plot. We also had more grass here than previously encountered. This is likely due to the exposed sun from the eastern side, as well as a slighter more open canopy that met our typical requirements. According to reports (2002 Upper River Raisin Plan), there have been few invasive species or other management activities in Nan Weston’s forest. Recent years have seen trail improvements and visitor access improvements (2006 Nature Conservancy stewardship report).

**Visited:** 7/16/20007  
**Name:** Smith Woods  
**City:** Scio Township, Village of Dexter  
**Class:** Exurban  
**Contact:** Allison Bishop, Community Development Manager

Official description:

“The Village's largest park, Smith Woods, is 17 acres of woodlands. Access is available off Dexter Chelsea Road. The park has some unimproved trails and backs up to the railroad tracks. Parking is available inside the gate. Smith Wood is the Village's largest park. The 17 acre park is undeveloped, although trails have been cleared throughout the wooded and otherwise undisturbed land.”

Notes:

There are wetlands throughout this wooded area. There is also a fairly wide (maybe 100m ) stretch of open area/water that separates this park's wooded edge from the road. We followed the path through the wetlands, to the base of a hill. Towards the northeast border of our plot, we were right next to the boundary of private property. Overgrown, untended paths were prevalent in these woods. At some point, they had likely been blazed, and then abandoned. This plot was along the Southeastern side of the hill, with the north west side of the plot 10 or 15 feet higher than the south east. No other visitors appeared in smith woods. Railroads were heard running by several times during the day.

The clearing at the opening of Smith Woods contains several bags of trash. Perhaps it is a popular dumping spot.

**Visited:** 7/18/2007  
**Name:** West Bloomfield Woods  
**City:** West Bloomfield  
**Class:** Suburban  
**Contact:** David Burley, Deputy Director, West Bloomfield Parks and Recreation

Official description:

“Though it is located in a bustling suburb only 20 miles from downtown Detroit, this beautiful 162-acre site could easily be mistaken for northern Michigan. Rolling hills covered with stately oak and hickory trees lead down into bottomland forest and wetland areas. In the spring, there are great carpets of white trillium and yellow trout lilies. The site is also home to large black walnut trees and beautiful native dogwoods. The nature preserve is the western trailhead of the West Bloomfield Trail Network, a 4.25-mile rails-to-trails project that meanders through areas of wildflowers, wetlands, woodlands, and residential communities. Bicycles are allowed on the trail network only.

“The primary attraction of this site is the active great blue heron rookery, which is easily visible near the west end of the trail network. The rookery overlook features a permanently mounted telescope for close-up viewing of approximately 100 great blue heron nests. Courtship begins in March and the nesting activity continues until the young leave the nesting area in early July. A 2.5-mile trail (1/2 mile of which is barrier free) wanders through the glacially sculpted hills and valleys of the nature preserve, which is frequented by over 100 bird species, white-tail deer, red fox, coyote, and weasels. Sightings of soaring turkey vultures, red-tailed hawks, and osprey are no longer rare.”

Notes:

Most of the accessible edge regions of the park were degraded, and did not contain sufficient canopy in order to set up a plot. Ultimately, we found the best success on the far southern edge of the site. Just south of the trails, and between two vernal pools, there was a large contiguous stretch of edge canopy off of North Red farm way. The terrain was tilted slightly towards the west, but was relatively flat. The general terrain sloped north, from the houses in to the preserve. We could frequently hear walkers and runners just over the ridge that separated the trail from our research plot. The park naturalist, Laurel Zoet, confirmed that no management takes place in West Bloomfield Woods other than the maintenance of

trails. If trees fall across the trail, they are chopped and thrown back in the woods. Numerous houses back up to the woods near our plot. As there are no lot markings, little differentiated the back of house lots and the beginning of the woods.

**Visited:** 7/20/2007  
**Name:** Tenhave Woods at Quickstad Park  
**City:** Royal Oak  
**Class:** Urban  
**Contact:** Bob Muller, Volunteer Naturalist

Official Description:

Quickstad Park is located between Normandy Road and Lexington Boulevard, several blocks east of Crooks. The total park acreage is 32.7, which includes the nature area, soccer fields, a hard surface walking path, and a dog run area. The park was dedicated on August 29, 1955. The arboretum at Quickstad has a long history of being utilized for education, but even with a high school located within a quarter mile of the park, there are no known classes utilizing the natural area. In 1967, a 4-year-old boy was killed in the woods at Quickstad Park. A 15-year-old mentally impaired youth was charged but not tried in the case. Many citizens demanded

the underbrush be razed. Others opposed the clearing, saying the park represented a 1,000-year-old forest too valuable to destroy. As a compromise, the fence surrounding the Park went up and residents could visit the Park only by getting a key at the City offices. In 1986, the City reopened the park by installing two turnstile gates that would be unlocked during daylight hours from May to October. The park is currently open all year. Tenhave Woods is also a densely forested area. The park is bordered by soccer fields along the west boundary and residential homes surround the remaining boundaries. The canopy cover is approximately ninety percent. There are a few natural openings that have come about as large, old growth trees have fallen down in storms.

Three stands are in the woods including: A lowland hardwood forest which includes red maple, silver maple, cottonwood, American elm, and green ash. An even-aged beech-maple stand. An even-aged oak hickory hardwood stand, which includes common tree species include shagbark hickory, bitternut hickory, white oak, red oak, sassafras, black cherry, ironwood, basswood and white ash. The recruitment of new trees in the shrub layer appears strongest with sugar maple and American beech trees in all stands. Emerald ash borers have infected and killed nearly all of the green and white ash trees within this park as well. Dutch elm disease has limited the size class of American elms to only small diameter trees.

Notes:

According to Bob Muller, "in the south west area of the park there is a vernal pond that was restored to its condition of 40 years ago by removing 68 trees in the fall of 2005. South and north of this pond buckthorn has been cut. There is still lot of it. This area of the park was still pasture land in 1940's and before with no trees. The south fence where there are houses has always been a forest this is the area you should set up. No buckthorn or garlic mustard has been removed from this area."



We worked in the southernmost part, just off the fence line, in an area in which no restoration work had been performed. However, all houses in the area had rear fence gates that opened into the forest. This was approximately several hundred meters away from the vernal pond restoration area. A lot of young sassafras was in the area.

**Visited:** 7/27/2007  
**Name:** George W. Suarez Friendship Woods  
**City:** Madison Heights  
**Class:** Urban  
**Contact:** Mathew Hackett, Naturalist

Official Description:

“Located in the middle of our developed community, the 37 1/2 acres of natural preservation known as George W. Suarez Friendship Woods leaves the patron wanting more. You are sure to leave refreshed and enlightened. With such a wide variety of nature opportunities for people to take advantage of, we hope you take time out to explore, relax, and enjoy nature. The 1 1/3 miles of paved trails surrounding the Nature Center are open 7 days a week, are perfect for a brisk walk or a casual stroll, and contain hawks, raccoons, squirrels, rabbits, many different wildflowers, trees, and birds.”

Notes:

Suarez Woods has northern and southern portions. The northern portion is highly degraded. The southern portion is generally high quality, although the recent loss of a significant number of ash trees has caused some changes in the composition.

According to the naturalist “In general, our park has one half which might be considered uncleared (but probably selectively cut in the 19th century), and another half which is pioneer growth beginning in the 1940's when it ceased to be farmland or neighborhood playfield.” The uncleared portion is the southern half in which we worked.

The southern half is characterized by a concrete loop that cuts through the park. It was estimated that the loop was at least a decade old, but there was no definite knowledge. Before the concrete loop, people occasionally would wander into the woods, but since its construction, that has ceased. A fence surrounds the entire southern portion of the park, so entry is restricted to the north side. The park was hit hard by the emerald ash borer. Approximately 1-2 years prior to our arrival, the park service removed all downed ash trees from the park. Other than that, no maintenance operations take place in the park. Generally, downed trees are thrown back into the woods. We set up on the east side of the park, with a north-south running transect. There was a bit of older trash in the area. Tenhave featured the single largest tree that we saw this summer.

## Tables

**Table 1: Density Classification used in Study Region**

<b>Housing Density Class</b>	<b>Land Acres per Housing Unit</b>
Urban	0.0 – 0.59
Suburban	0.60 – 2.99
Exurban	3.00 – 9.99
Rural	10+

(Taylor 2008)

The density classification scheme was applied to each census block group in the study region. To calculate land area, hydrologic feature data were acquired from the Michigan Geographic Data Library (Michigan Center for Geographic Information 2008). The hydrologic features within each block group were then subtracted from that block group's total area in order to produce land area. Total housing units in each census block group were acquired from Census 2000 data. Land acres / housing unit (LA/HU) was calculated by dividing land acres by housing units in each census block group.

**Table 2: Study Sites, Classes, and Locations**

<b>Housing Density</b>	<b>Site Name</b>	<b>Municipality</b>	<b>Abbreviation</b>
Urban	Suarez Friendship Woods	Madison Heights	SFW
Urban	Tenhave Woods at Quickstad Park	Royal Oak	TW
Urban	Valley Woods	Southfield	VW
Suburban	West Bloomfield Woods	Bloomfield	WBW
Suburban	Saginaw Woods	Scio	SAG
Suburban	Black Pond Woods	Ann Arbor	BPW
Exurban	Smith Woods	Scio Township, Village of Dexter	SW
Exurban	Pittsfield Preserve	Pittsfield	PP
Exurban	Osborne Mill	Scio	OSM
Rural	E.S. George Reserve	Putnam	ESG
Rural	Lefurge Woods Preserve	Superior	LW
Rural	Nan Weston Nature Preserve	Sharon Hollow	NWN

Housing density class is based on the previously described scheme (Table 1). Each site was ascribed the density of the census block group which it directly overlaid.

**Table 3: Relationship Between Housing Density and % N in Soil****A. Summary Linear Regressions on Mean Soil %N**

Independent Variable	Coefficients (p)	R <sup>2</sup>	Model Significance (p)
Log <sub>e</sub> LA/HU 100 m scale	-0.02 (0.09)	0.26	0.09
Log <sub>e</sub> LA/HU 1,000 m scale	-0.02 (0.08)	0.27	0.08
Log <sub>e</sub> LA/HU 10,000 m scale	-0.02 (0.13)	0.21	0.13
% Sand	-1.3 x10 <sup>-3</sup> (0.17)	0.09	0.17
Log <sub>e</sub> LA/HU 100 m scale x % Sand	-3.3x10 <sup>-4</sup> (0.01)	0.48	0.01
Log <sub>e</sub> LA/HU 1,000 m scale x % Sand	-3.3x10 <sup>-4</sup> (0.01)	0.47	0.01
Log <sub>e</sub> LA/HU 10,000 m scale x % Sand	-4.5x10 <sup>-4</sup> (0.01)	0.47	0.01

**B. Linear Mixed Model on Soil % N**

Independent Variables	Coefficients (p)	Model AIC (smaller is better form)	χ <sup>2</sup> Fit Test: improvement over null (p value)
Intercept Only (null)	-----	-131.47	-----
Log <sub>e</sub> LA/HU 100 m scale	-0.02 (0.01)	-141.31	< 0.01
Log <sub>e</sub> LA/HU 1,000 m scale	-0.02 (0.01)	-140.82	< 0.01
Log <sub>e</sub> LA/HU 10,000 m scale	-0.03 (0.03)	-138.90	< 0.01
% Sand	-1.0x10 <sup>-3</sup> (0.06)	-133.03	0.16
Log <sub>e</sub> LA/HU 1,000 m scale, % Sand	-0.02 (< 0.01), -8.1x10 <sup>-4</sup> (0.06)	-142.44	< 0.01
Log <sub>e</sub> LA/HU 1,000 m scale x % Sand	3.4x10 <sup>-4</sup> (< 0.01)	-144.63	< 0.01

The relationship between housing density in the surrounding landscape and soil nitrogen concentration in a protected area is shown using a linear regression on the site mean values, and a linear mixed model on all samples. Data were derived from 12 field study plots in the present study. Log<sub>e</sub> land acres / housing unit (LA/HU) is used as a proxy for housing density. Model coefficients and p values are listed for all statistical tests. R<sup>2</sup> and p values are listed for linear regressions, while Akaike's Information Criteria (AIC) allows relative comparison of linear mixed models. The χ<sup>2</sup> goodness of fit test indicates whether a model is a significant improvement over another model. In this case, all models are compared against the null model.

**Table 4: Relationship between Housing Density and Soil C/N ratio****A. Summary Linear Regressions on Mean Soil C/N**

Independent Variables	Coefficients (p)	R <sup>2</sup>	Model Significance (p)
Log <sub>e</sub> LA/HU 100 m scale	0.12 (0.60)	0.03	0.60
Log <sub>e</sub> LA/HU 1,000 m scale	0.09 (0.71)	0.01	0.71
Log <sub>e</sub> LA/HU 10,000 m scale	0.21 (0.51)	0.04	0.51
Log <sub>e</sub> LA/HU 1,000 m scale x % Sand	2.1x10 <sup>-3</sup> (0.52)	0.04	0.52

**B. Linear Mixed Model on Soil C/N**

Independent Variables	Coefficients (p)	Model AIC (smaller is better form)	χ <sup>2</sup> Fit Test: improvement over null (p value)
Intercept Only (null)	-----	179.069	-----
Log <sub>e</sub> LA/HU 1,000 m scale	-0.05 (0.83)	181.037	0.98
Log <sub>e</sub> LA/HU 1,000 m scale, % Sand	-0.06 (0.79), -2.7x10 <sup>-3</sup> (0.86)	183.022	0.98
Log <sub>e</sub> LA/HU 1,000 m scale x % Sand	2.3 x 10 <sup>-3</sup> (0.95)	181.066	0.99

The relationship between housing density in the surrounding landscape and soil carbon / nitrogen ratio in a protected area is shown using a linear regression on the site mean values (A), and a linear mixed model on all samples (B). Data were derived from 12 field study plots in the present study. Log<sub>e</sub> land acres / housing unit (LA/HU) is used as a proxy for housing density. Model coefficients and p values are listed for all statistical tests. R<sup>2</sup> and p values are listed for linear regressions, while Akaike's Information Criteria (AIC) allows relative comparison of linear mixed models. The χ<sup>2</sup> goodness of fit test indicates whether a model is a significant improvement over another model. In this case, all models are compared against the null model.

**Table 5: Relationship between Mean Soil and Foliar Nitrogen**

<b>Independent</b>	<b>Dependent</b>	<b>Coefficient</b>	<b>R<sup>2</sup></b>	<b>p</b>
Soil % N	Foliar % N	0.93	0.09	0.35
Soil % N	Foliar C/N Ratio	-9.67	0.11	0.30
Soil C/N Ratio	Foliar % N	-0.05	0.09	0.33
Soil C/N Ratio	Foliar C/N Ratio	0.58	0.18	0.17

Data were derived from 12 field study plots in the present study. Coefficients, R<sup>2</sup>, and p values are listed for linear regressions between each pair of independent and dependent variables listed.

**Table 6: Relationship between Topographic/Geologic Controls and N in Soil****A. Linear Regressions on Mean Soil % N**

Independent Variables	Coefficients (p)	R <sup>2</sup>	Model Significance (p)
Elevation	$3.3 \times 10^{-4}$ (0.01)	0.52	0.01
Elevation, % Sand	$3.8 \times 10^{-4}$ (< 0.01), $-1.8 \times 10^{-3}$ (< 0.01)	0.82	< 0.01
Wetness, % Sand, Aspect	0.03 (0.01) $-2.2 \times 10^{-3}$ (0.01) $-1.2 \times 10^{-4}$ (.199)	0.72	0.01

**B. Linear Mixed Model on Soil % N**

Independent Variables	Coefficients (p)	Model AIC (smaller is better form)	Chi Squared Fit Test: improvement over null (p value)
Intercept Only (null)	-----	-131.467	-----
Elevation	$-2.7 \times 10^{-4}$ (< 0.01)	-137.368	0.02
Elevation, Sand	$-3.3 \times 10^{-4}$ (< 0.01) $-1.5 \times 10^{-3}$ (< 0.01)	-148.086	< 0.01
Topographic Index of Wetness	$6.1 \times 10^{-3}$ (0.15)	-131.416	0.38
% Sand	$-1.0 \times 10^{-3}$ (0.06)	-133.030	0.17
Aspect	$-3.9 \times 10^{-5}$ (0.67)	-129.646	0.89
Wetness, % Sand, Aspect	0.01 (< 0.01) $-1.6 \times 10^{-3}$ (< 0.01) $-9.9 \times 10^{-5}$ (0.12)	-138.922	0.01

**C. Linear Regressions on Mean Soil C/N Ratio**

Independent Variables	Coefficients (p)	R <sup>2</sup>	Model Significance (p)
Elevation	$2.5 \times 10^{-3}$ (0.44)	0.06	0.44
Wetness, % Sand, Aspect	-0.25 (0.29) 0.03 (0.27) $3.7 \times 10^{-3}$ (0.26)	0.29	0.42

The relationship between topographic / geologic aspects of the surrounding landscape and soil nitrogen content in 12 field plots across the study region is shown. Data were derived from 12 field study plots in the present study. Model coefficients and p-values are listed. R<sup>2</sup> and p values are listed for linear regressions (A and C), while Akaike's Information Criteria (AIC) allows relative comparison of linear mixed models (B). The  $\chi^2$  goodness of fit test indicates whether a model is a significant improvement over another model. In this case (B), all models are compared against the null model.

**Table 7: Relationship between Ground-cover and Housing Density****Linear Regressions upon Site Means**

<b>Independent Variables</b>	<b>Dependent Variable</b>	<b>Coefficient</b>	<b>R<sup>2</sup></b>	<b>p</b>
Log <sub>e</sub> LA/HU 1,000 m scale	% Bare	-2.37	0.04	0.53
Log <sub>e</sub> LA/HU 1,000 m scale	% Woody	0.74	0.01	0.76
Log <sub>e</sub> LA/HU 1,000 m scale	% Forbs	1.34	0.02	0.64
Soil % N	% Bare	-72.00	0.05	0.50
Soil % N	% Woody	108.74	0.25	0.10
Soil % N	% Forbs	-17.98	0.01	0.82

Data were derived from 12 field study plots in the present study. Coefficients, R<sup>2</sup> and p values are listed for linear regressions between each pair of independent and dependent variables listed.



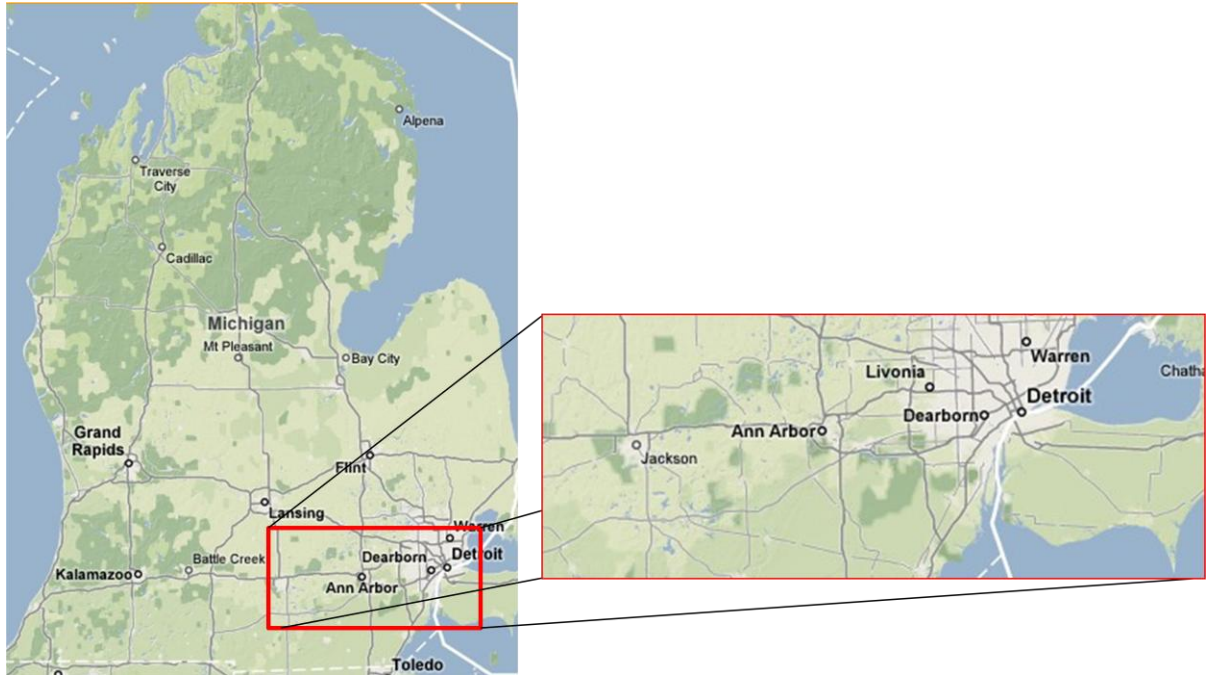
**Table 8: Foliar Chemistry Sample Summary**

<b>Genus</b>	<b># of Samples</b>	<b>Mean % C</b>	<b>Mean % N</b>	<b>Mean C/N Ratio</b>
<i>Acer</i>	42	44.55	1.94	23.85
<i>Aesculus</i>	1	45.37	2.28	19.90
<i>Carpinus</i>	7	44.28	1.88	23.64
<i>Carya</i>	22	41.92	2.02	20.92
<i>Cornus</i>	5	41.50	2.01	20.93
<i>Fagus</i>	7	46.32	2.45	19.00
<i>Fraxinus</i>	22	42.94	2.22	19.74
<i>Hammamelis</i>	5	45.01	1.74	26.17
<i>Malus</i>	6	43.28	1.53	28.71
<i>Ostrya</i>	15	43.78	1.98	22.23
<i>Prunus</i>	39	43.35	2.26	19.92
<i>Quercus</i>	24	44.28	2.16	20.67
<i>Rhamnus</i>	7	40.16	3.31	12.16
<i>Robinea</i>	1	40.06	2.95	13.60
<i>Sassafras</i>	2	42.98	2.62	16.46
<i>Tilia</i>	11	41.98	2.59	16.45
<i>Ulmus</i>	24	42.25	2.15	19.92
<i>Viburnum</i>	1	42.78	2.36	18.14

Foliar sample data are presented with number of samples, mean % carbon by mass, mean % nitrogen by mass and mean C/N ratio by mass. Data were derived from 12 field study plots in the present study.

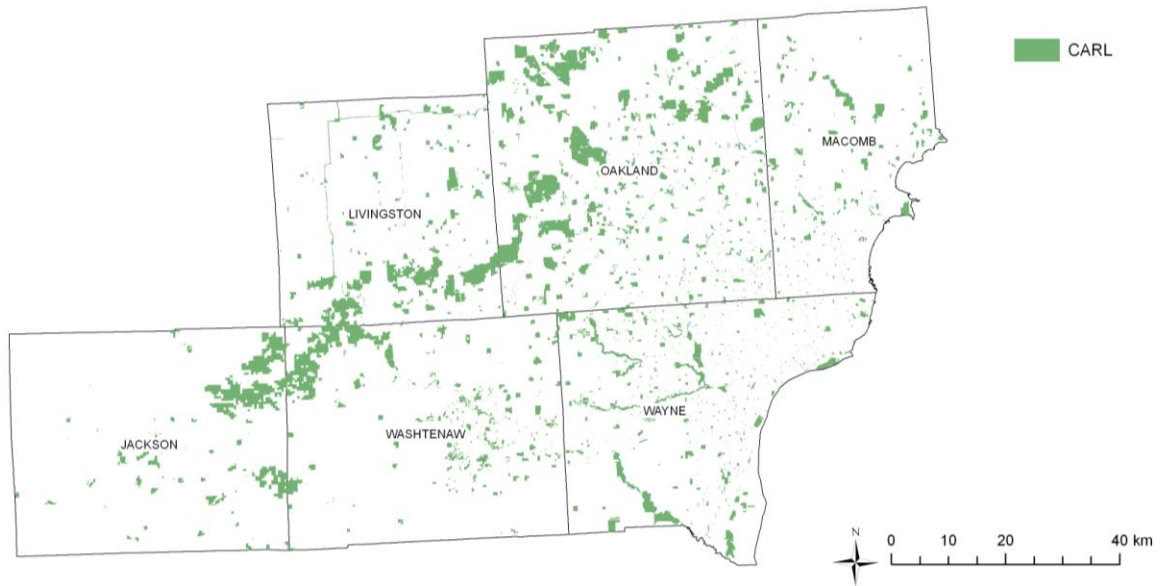
## Figures

Figure 1: Location of Southeastern Michigan



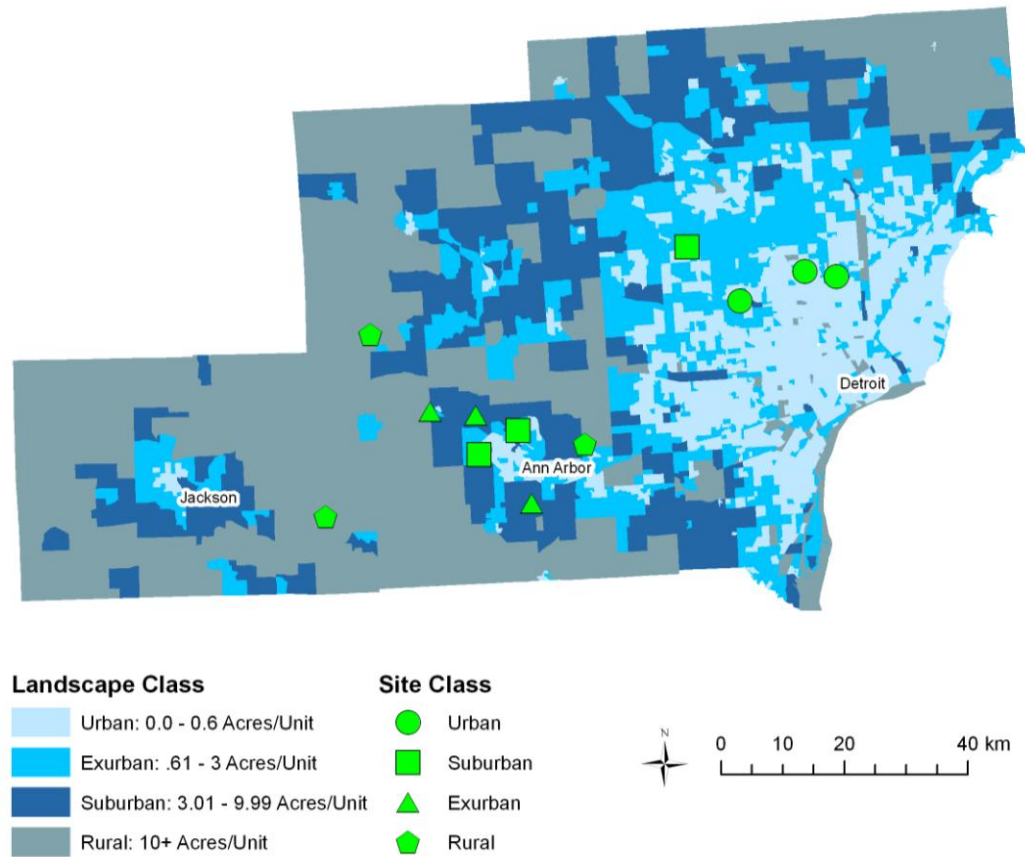
Lower Michigan, with Southeastern Michigan highlighted and expanded.  
Map image from Google Maps (Google 2008).

**Figure 2: Study Geographic Extent with County Boundaries and CARL Areas Imposed**

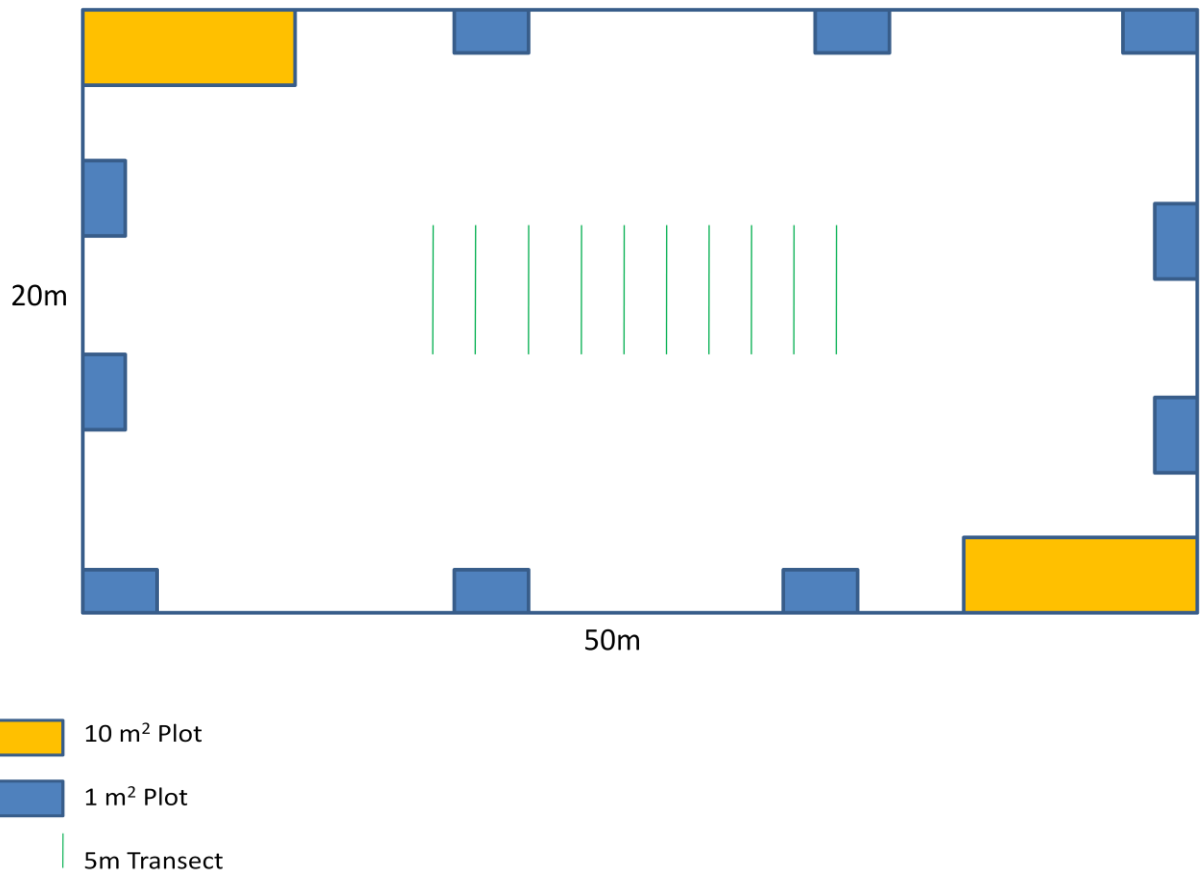


Map shows the Ducks Unlimited Conservation and Recreation Lands (CARL) data layer imposed upon the six county study region in Southeastern Michigan, USA. County names and boundaries are shown (Michigan Center for Geographic Information 2008; Wilcox & Macleod 2008).

**Figure 3: Map of Housing Density, Major Cities, and Site Locations**

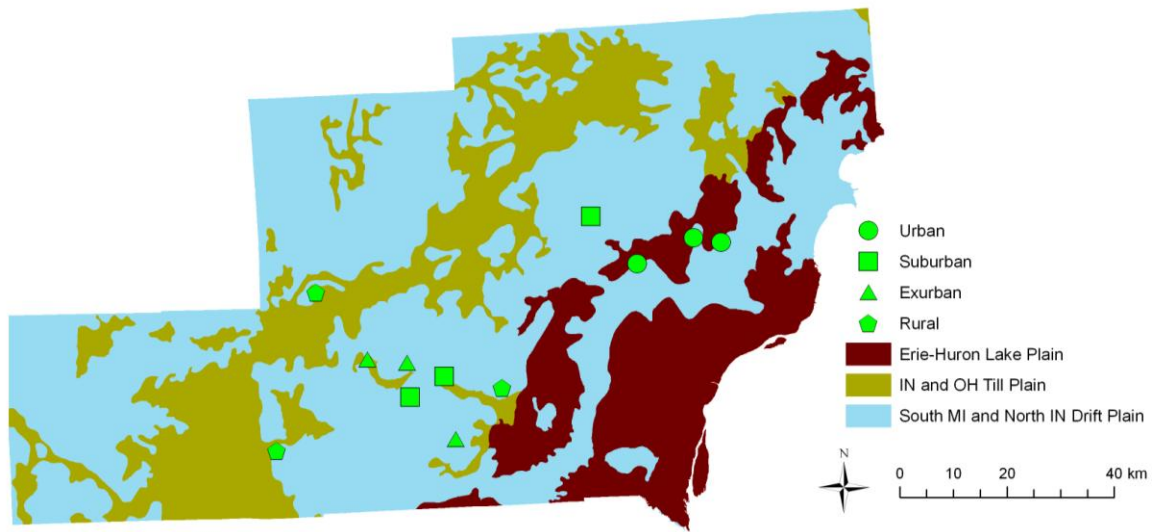


Both maps show housing density (acres / unit) in census block group resolution across the study extent. The names of the three major metropolitan areas are shown, as well as site locations from the current study. Sites are shape coded by housing density classification (Michigan Center for Geographic Information 2008; US Census Bureau 2008).

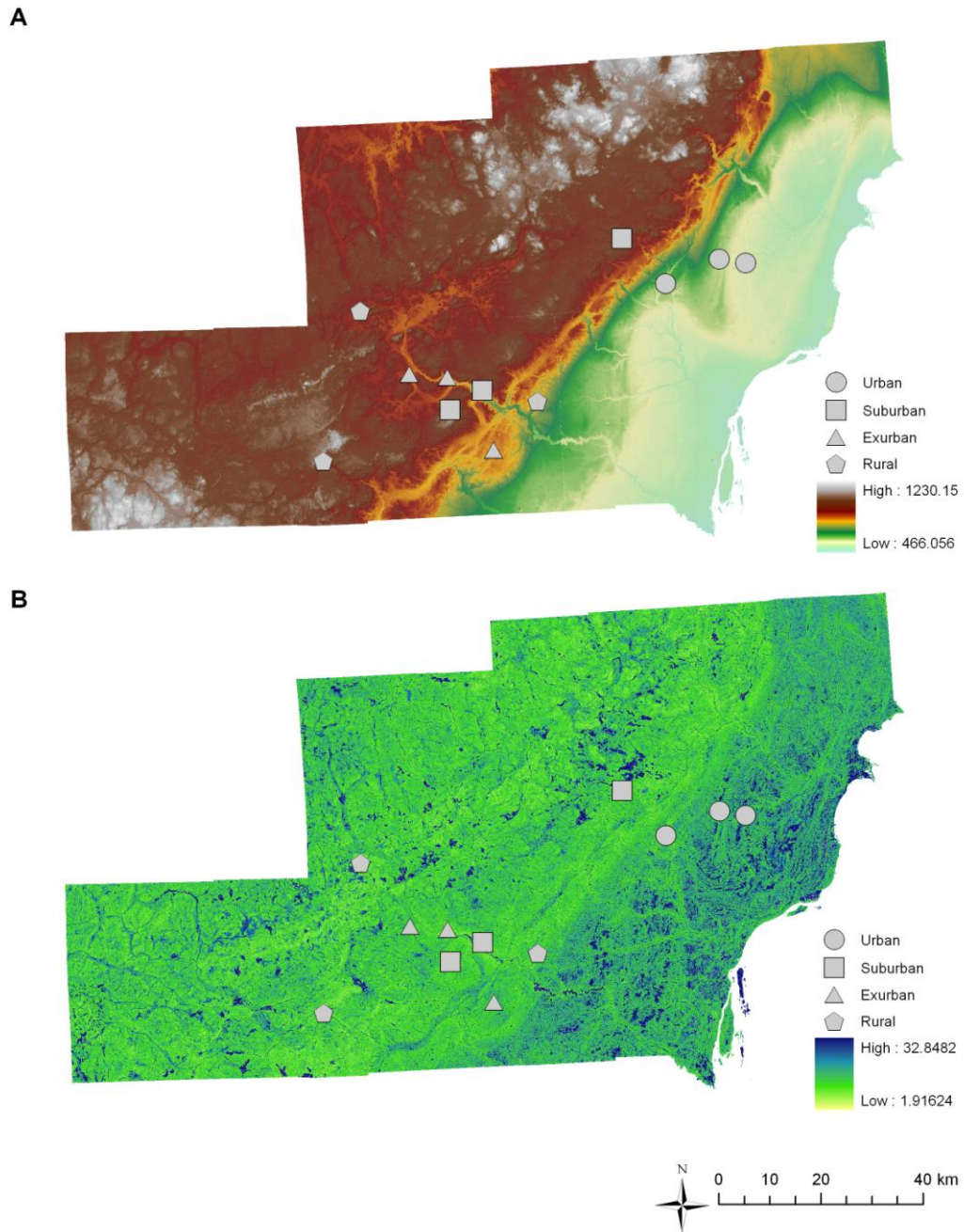
**Figure 4: Research Plot Design**

This research plot was placed ten meters from the edge of each site. Ground-cover was assessed in the 1 m<sup>2</sup> plot, in the 10 m<sup>2</sup> plot, and along the 5 m transect. Woody plants were then identified for the whole plot. Plot design was primarily based on Stohlgren's design (Stohlgren et al. 1995; Stohlgren 2007).

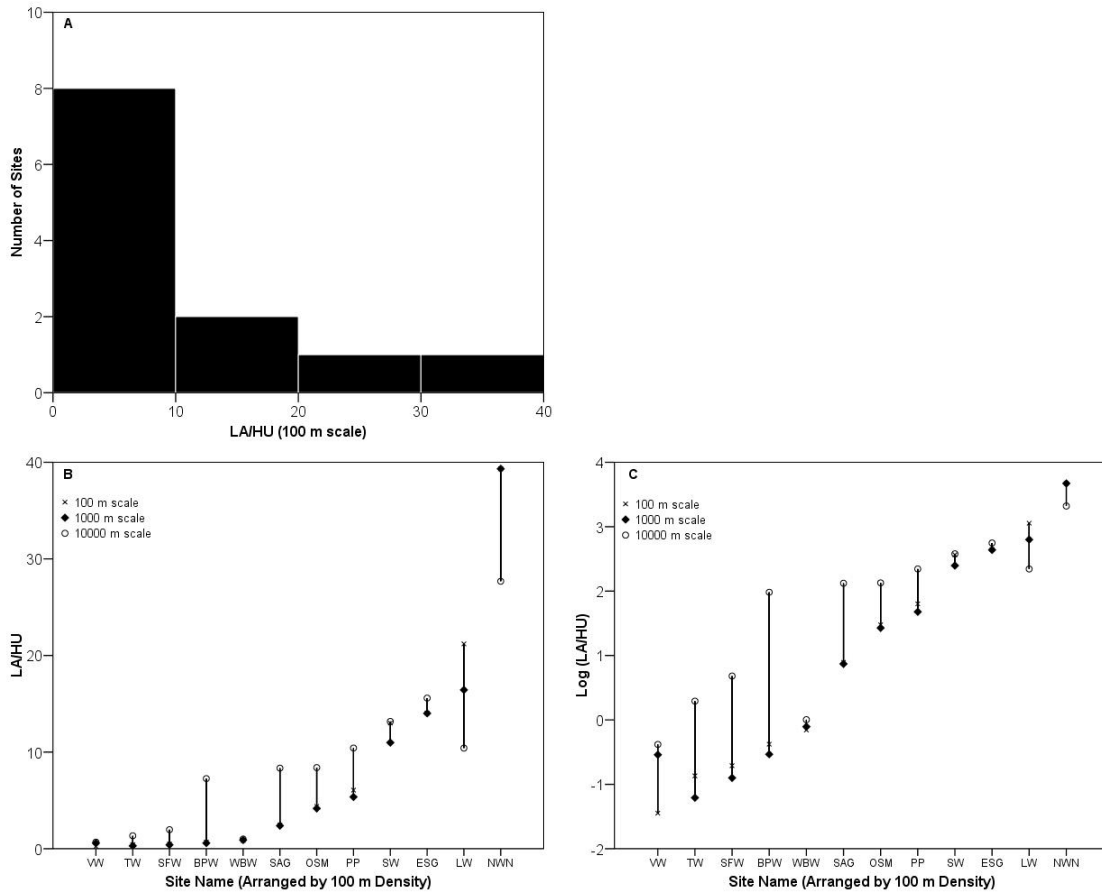
**Figure 5: Soil Classes in Southeastern Michigan**



Research site locations are shown and overlaid upon the soil orders from across the study region. (National Resources Conservation Service 2008).

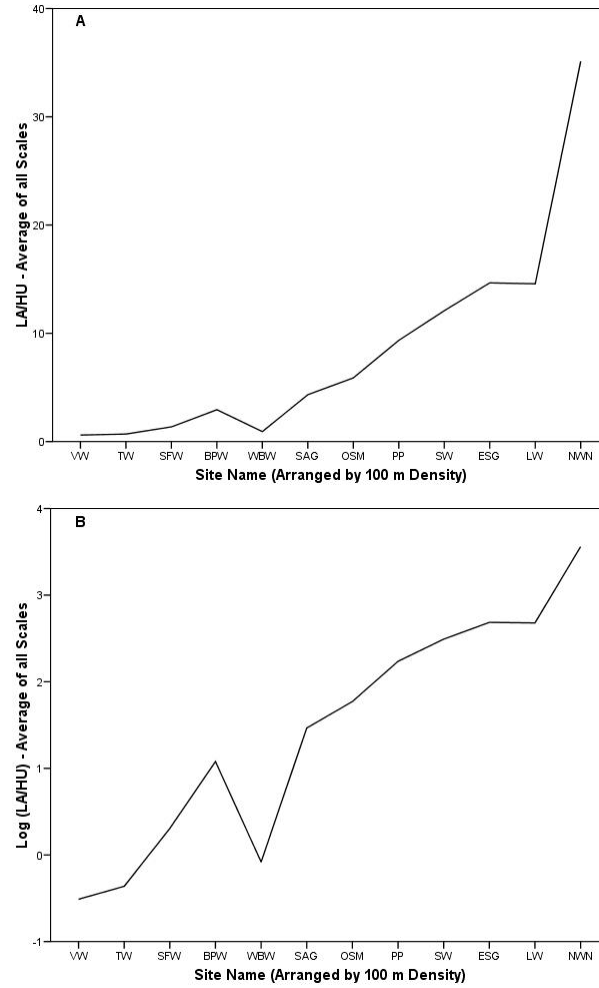
**Figure 6: Southeastern MI Elevation and Topographic Index of Wetness**

The study region's digital elevation map (A) and topographic index of wetness (B) are shown with research site locations imposed (Michigan Center for Geographic Information 2008).

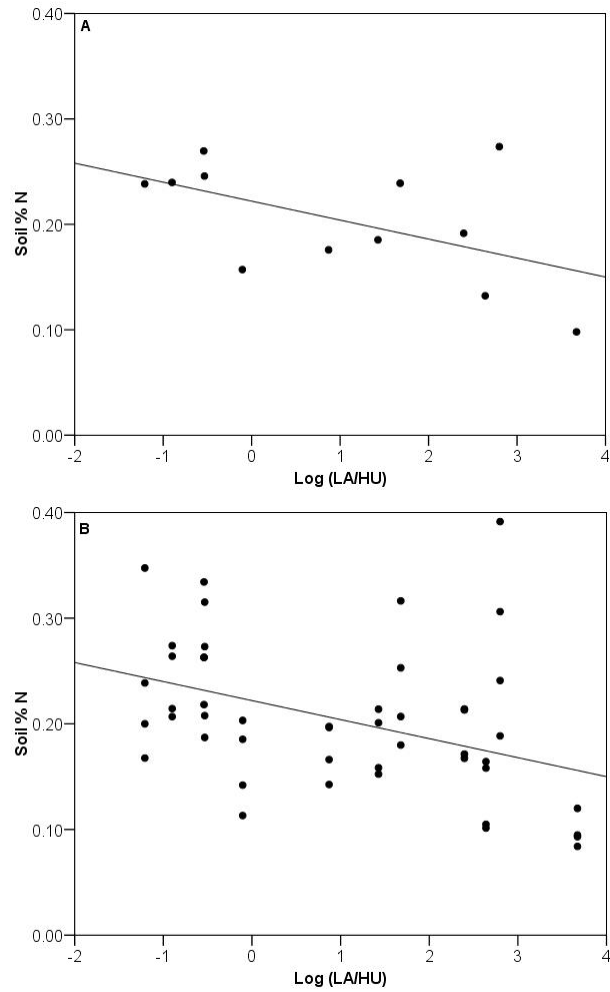
**Figure 7: Distributions of Sites across Housing Densities**

Land acres per housing unit (LA/HU) was calculated as a proxy for housing density in the landscape surrounding each of the 12 research sites. Abbreviated site names are as in Table 2. A smaller value indicates a higher housing density. Starting at the centroid of each plot, housing density was calculated in circles with 100 m, 1,000 m, and 10,000 m radii. The distribution of housing densities is left skewed when calculated at the 100 m scale (A). The skew persists through all scales (B). A  $\log_e$  transform was performed on the data (C), which produced a more linear pattern.

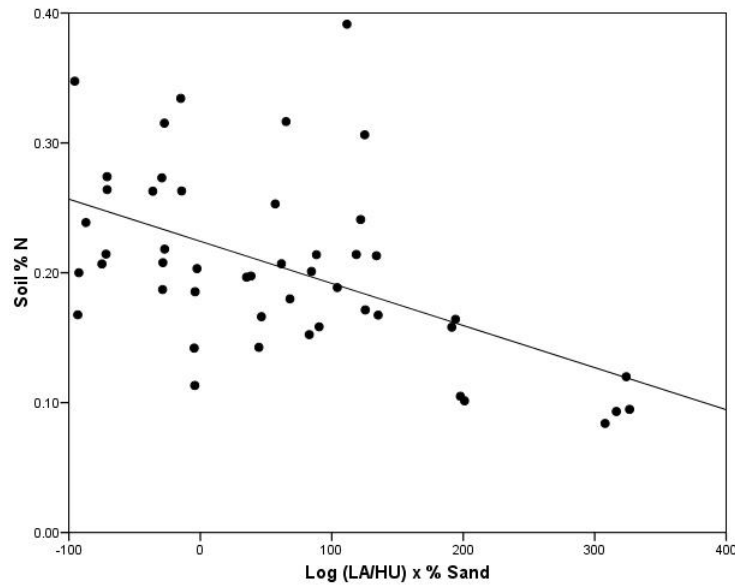


**Figure 8: Average Housing Densities**

An average of mean land acres per housing unit (LA/HU) at all scales (100 m, 1,000 m, 10,000 m) was calculated. LA/HU is an inverse measure of density, so lower values indicate higher density. If density were consistent at all scales, the line would smoothly increase from left to right. Untransformed (A) and  $\log_e$  LA/HU (B) are shown. Site abbreviations are consistent with Table 2.

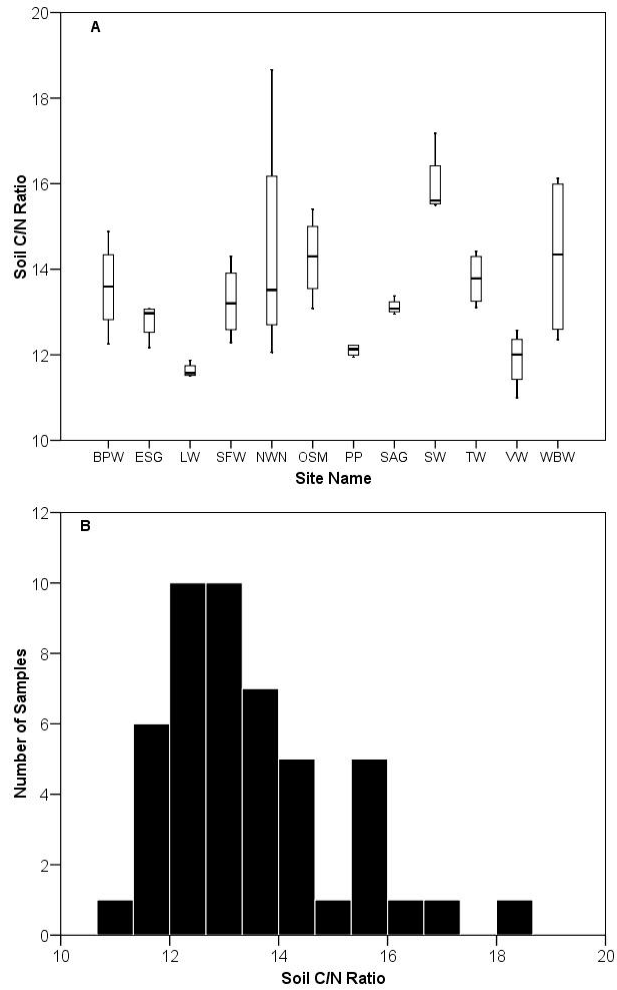
**Figure 9: Comparison Graphs of Mean Site Soil % N and All Samples**

Mean soil N concentration in the 12 study sites is plotted against mean log<sub>e</sub> land acres per unit (LA/HU) in the surrounding landscape (A). All samples are also shown (B). A negative relationship ( $R^2 = 0.27$ ) was found between 1,000 m scale log<sub>e</sub> (acres/unit) and % N in soil, indicating that % N in soil increases with housing density.

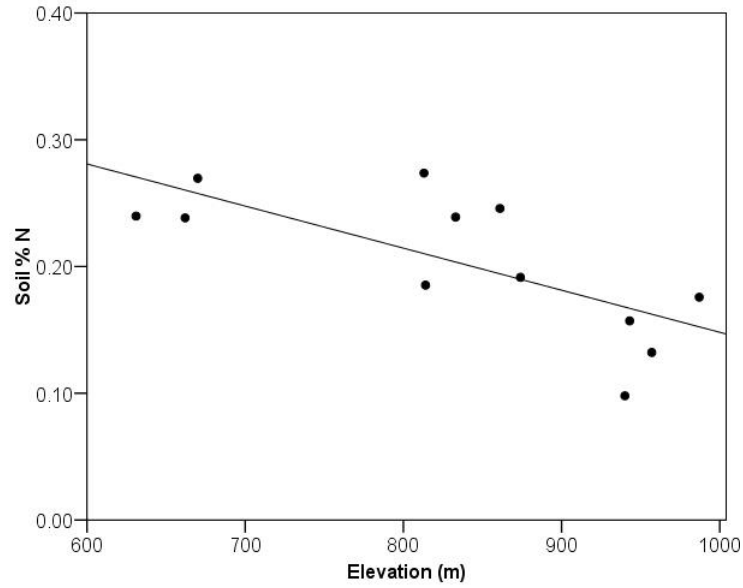
**Figure 10: N Concentration in Soil vs. Interaction of loge (LA/HU) and % Sand**

The effect of housing density on soil nitrogen concentration may be driven by the texture of the soil. A linear regression on the site mean nitrogen concentration (not shown) shows high statistical significance ( $R^2 = 0.47$ ,  $p = .01$ ). In order to emphasize the internal site variability, all soil samples from the 12 study sites are shown here. The housing density proxy is represented as  $\log_e$  land acres per housing unit (LA/HU).

**Figure 11: Distribution of Soil C/N Across Sites and Study Area**

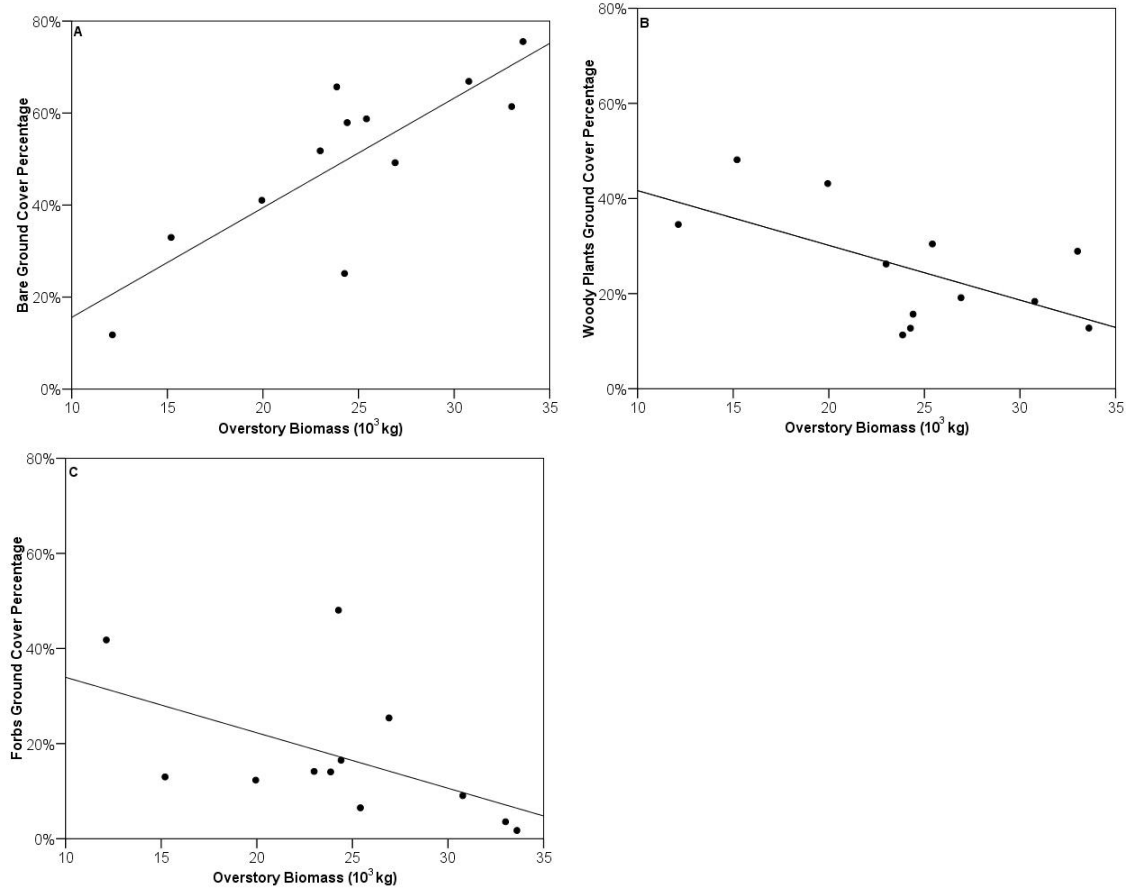


Mean, quartile, and standard deviation of soil C/N ratio (by mass) in the 12 study sites is shown (A). Soil samples were taken by sweeping away leaf litter, then taking 17 cm deep sample. Site abbreviations follow Table 2. The study region possessed a mean C/N ratio of 13.43 with a standard deviation of 1.59 (B).

**Figure 12: The Relationship between N content in Soil and Elevation**

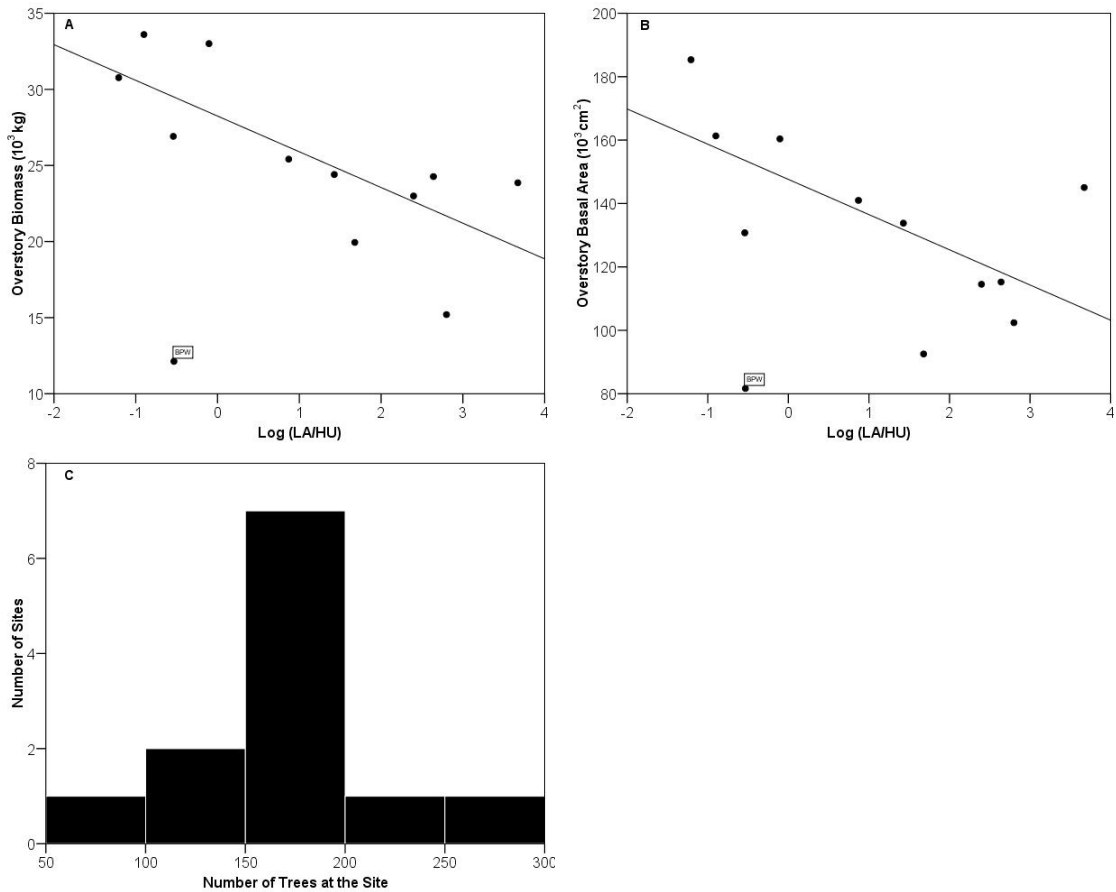
Plot elevation is a strong predictor of mean site N content ( $R^2 = 0.52$ ,  $p < 0.01$ ) in the twelve study sites.

**Figure 13: Linear Regressions between Overstory Biomass and Ground-cover**



Statistically significant relationships are found between overstory biomass, percent bare ground-cover (A,  $R^2 = 0.67$ ,  $p < 0.01$ ) and percent woody plant ground-cover (B,  $R^2 = 0.37$ ,  $p = 0.04$ ). The relationship between woody biomass and forb cover is insignificant (C,  $R^2 = 0.28$ ,  $p = 0.08$ ). An increase in overstory biomass correlates with an increase in bare ground-cover, and a decrease in woody ground-cover.

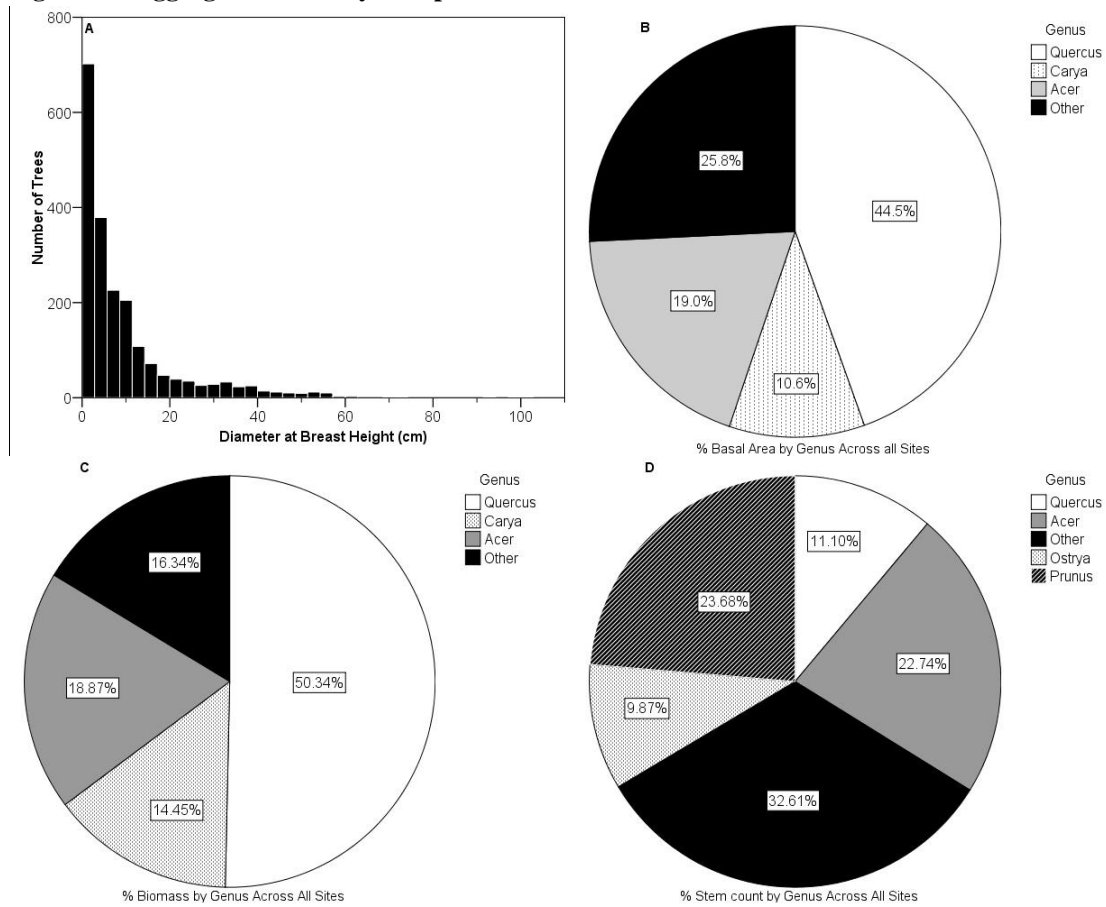
**Figure 14: Relationship between Overstory and Housing Density**



Black Pond Woods (identified in A and B) has the fewest tree stems, the least biomass, and least basal area out of the 12 study sites. As an outlier with less than 50% the mean stem count, it was excluded from the site biomass and basal area analyses.

Regression lines are imposed upon plots of  $\log_e$  land acres per housing unit (LA/HU) versus woody plant overstory biomass (A,  $R^2 = 0.60$ ,  $p < 0.01$ ) and basal area (B,  $R^2 = 0.44$ ,  $p = 0.03$ ). 7 of 12 sites had between 150 and 200 tree stems (C).

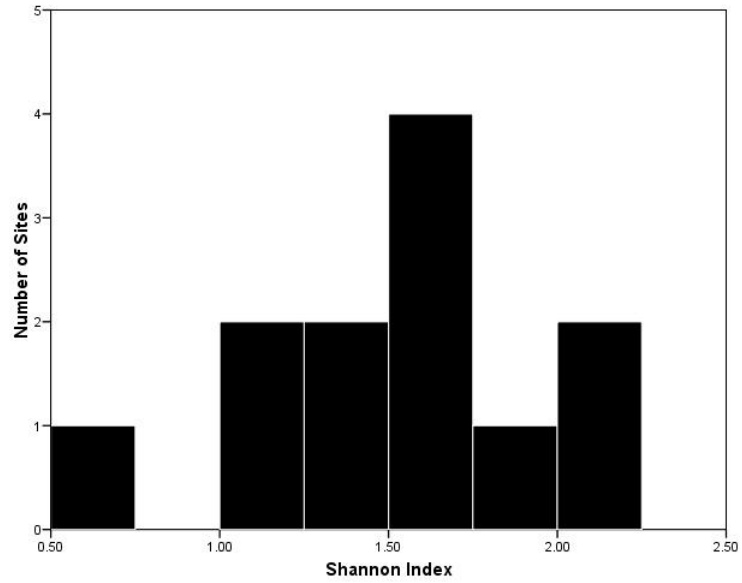
Figure 15: Aggregate Overstory Composition Results



2,027 tree stems were encountered in the twelve study plots. Approximately 700 were beneath 3 cm in diameter at breast height (A). Basal area was dominated by *Quercus*, *Carya* and *Acer* (74.1%, B). Biomass was similarly composed of primarily *Quercus*, *Carya* and *Acer* (83.7%, C). Many of the smaller woody plants dominated the stem count, including *Ostrya* (22.74%) and *Prunus* (23.68%).



**Figure 16: Histogram of Shannon Index by Site Frequency**



Shannon index, which is a commonly used metric of biodiversity, was calculated by genus for the woody plants at each site. Values ranged from 0.68 to 2.17, with higher values indicating a more even distribution of genera among all woody plants.

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