STRATEGIES FOR ENHANCING CARBON SEQUESTRATION AND CO-BENEFITS IN HUMAN DOMINATED LANDSCAPES

By

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Abstract

The design and management of exurban residential properties offers an immense opportunity to impact carbon storage and sequestration because of the large amount of land these subdivisions occupy. This thesis addresses the gap between the science investigating the carbon cycle in human dominated landscapes, and the on-the-ground decisions made by designers and land managers. Based on a review of the literature addressing carbon cycling in vegetated, urban, and agricultural land uses under different management and climate regimes, we crafted strategies to help planners and designers optimize carbon storage in a way that is consistent with other potential ecosystem services, human functional requirements and cultural expectations in metropolitan landscapes.

Then we used these strategies as metrics to assess the carbon storage performance of two well-known conservation subdivisions: Prairie Crossing in Grayslake, Illinois, a 678-acre development with 359 single family homes and 36 condominiums, and Coffee Creek in Chesterton, Indiana, a 700-acre development with plans for 3000 residential units and 4 million square feet of commercial space. Based on data derived from a review of the existing literature describing each site, publically available data from the developers of each site, as well as conversations with their designers, developers and land managers, we assessed the success of these developments in preserving and enhancing carbon sequestration. We found that many of our strategies for carbon storage overlapped with the conservation principles used in designing these subdivisions, but that shifts in construction and management practices could increase the potential for carbon storage in these developments, especially on private residential land.

Finally, the carbon storage strategies are applied to the design of an ecological restoration plan, a conservation subdivision, and individual yard treatments for an exurban subdivision in a post-industrial city with a temperate climate.

Chapter I

Introduction

Problem statement

" Human actions have been a primary cause of the climate changes observed today. Fortunately, though, humans are also capable of changing their behavior in ways that can reduce the rate of future climate change and help wild species adapt to climate changes that cannot be avoided."

- *Ecological Impacts of Climate Change, National Academies of Science (Johnson 2009)*

In *Climate Change 2007: Impacts, Adaptation and Vulnerability*, the Intergovernmental Panel on Climate Change (IPCC) concluded that anthropogenic sources of greenhouse gases have contributed discernibly to climate changes, particularly increasing temperatures. These shifts in climate have in turn impacted natural and biological systems, including hydrology and water resources and stability of regions of frozen ground, snow and ice. Rising water levels and earlier flush in rivers impacted by snowmelt are leading to destruction of costal wetlands and mangroves. Regions with frozen ground, snow and ice are experiencing increased frequency of rock avalanches, instability in permafrost, and increased chances of outburst flooding from enlarging glacial lakes. Terrestrial ecosystems are also being impacted by shifts in the global climate. Increasing temperatures, earlier onset of spring, and an increase in the duration of the growing season are leading to species migration towards the poles and into higher elevations (Parry *et al.* 2007).

The IPCC asserts that a combination of mitigation and adaptation measures can help to minimize the impacts of climate change on natural and human systems. Mitigation activities, including new policies, economic instruments, technologies, institutional controls and behavioral shifts will not have perceptible benefits until the mid 21st century, but can ultimately lead to future stabilization of green house gases. Meanwhile, effective adaptation measures, including water management, shifts in agricultural regimes, and disaster risk management can help to minimize immediate effects of shifting climates (Parry *et al.* 2007)

Exurban subdivisions for climate change adaptation and mitigation

Accounting for one-third of all anthropogenic carbon emissions since 1750, land cover change is a substantial contributor to climate change (Solomon *et al.* 2007). In the early half of the 20th century, the majority of land cover shift in the United States was from wildland or lands dedicated to resource extraction to urban or suburban housing and agriculture. In the later half of the century, however, people in the United States began moving from city centers and suburbs to low-density rural subdivisions on land that was previously used for forestry or agriculture (Hansen *et al.* 2005). The area of land occupied by these exurban residential developments in the United States has increased by 500% since 1950, and in 2000 occupied more than 15 times the land area of more urbanized development types (Brown *et al.* 2005).

The large amount of land area occupied by exurban residential neighborhoods presents both challenges and opportunities for ecosystem services. A study conducted by Hansen et al (2005) examined two case studies of exurban developments for their impacts on biodiversity in Washington and Colorado, U.S.. They found that native vegetation biodiversity and survival tended to decrease when exurban housing density increased, and that ecosystems surrounding exurban developments tended to include more early succession and non-native species than they did prior to exurban development (Hansen *et al.* 2005). These results imply that without careful and intentional planning, the expansion of exurban residential land uses could have a negative impact on species diversity in native ecosystems. Despite this potentially negative relationship, the expanse of land occupied by exurban neighborhoods makes them integral to planning for functioning ecological systems and increased carbon sequestration and pool size in human dominated landscapes. The design and planning of exurban neighborhoods offers an opportunity to impact ecosystem services including habitat maintenance for biodiversity and water management, as well as climate change adaptation and carbon sequestration, the latter contributing to climate change mitigation at a regional scale.

Concept

The premise of this thesis is that exurban residential developments offer a unique opportunity to impact climate change through carbon sequestration and storage in vegetation and soils while simultaneously serving other ecosystem functions such as habitat creation and maintenance and stormwater mitigation. Because of this unique opportunity, it is key to combine the science behind carbon sequestration with the sensitivity to human preferences that is such an important aspect of design. This thesis seeks to provide designers and land managers with rules-of-thumb that should be followed in order to enhance carbon sequestration and storage in human dominated landscapes in the temperate biomes of North America, then demonstrate the application of those guiding principles.

The following is a brief outline of the strategy that will be taken in this thesis to develop and apply design guidelines for carbon sequestration. A literature review of the science of carbon sequestration as it applies to agriculture, intact ecosystems, and built landscapes will inform a set of design rules-of-thumb for human dominated landscapes. These rules-of-thumb will then be used to critically analyze two celebrated conservation subdivisions through the lens of carbon sequestration: Prairie Crossing in Grayslake, Illinois and Coffee Creek in Chesterton, Indiana. Finally, these guidelines will be applied to the creation of four designs for an unfinished subdivision in a post-industrial city: a conservation subdivision that creates a desirable neighborhood while following the guidelines for carbon sequestration, an ecological restoration plan for the subdivision at its current level of construction with an emphasis on carbon sequestration, and a design for a set of six yards and an individual yard that could fit into the subdivision as it stands or in a full build out scenario.

Chapter II

Literature Review

The potential of ecosystems to sequester and store carbon

The carbon stored in the terrestrial biosphere is in constant flux, and is influenced by anthropogenic processes such as deforestation, soil disturbances, fire and reforestation and natural processes such as fire, vegetation growth, reforestation, soil disturbances, and respiration. Since 1750, these processes have contributed to the terrestrial biosphere absorbing about 30% of all anthropogenic and natural carbon emissions (Solomon *et al.* 2007). Certain terrestrial ecosystems contribute to carbon sequestration more than others based on differences in plants and soils. In the United States, the largest pools of carbon include temperate grasslands, temperate forests, and wetlands (Table 1) (Watson *et al.* 2000).

Table 1: Gigatons of carbon in global terrestrial ecosystems (Watson *et al.* 2000)

Ecosystem Type	Carbon in Soils (Gt)	Carbon in Vegetation (Gt)	Total Caron (Gt)
Temperate forests	100	59	159
Temperate Grasslands	295	9	304
Wetlands	225	15	240
Croplands	128	3	131

The way that these terrestrial ecosystems contribute to the carbon cycle will change as carbon levels in the atmosphere rise. While outlining a research strategy for quantifying the relationship between global climate change and terrestrial ecosystems, Amthor and Huston (1998) proposed how several generalized ecosystem types categorized by climate, flora and fauna might react to increased atmospheric carbon levels (Table 2) (Amthor and Huston 1998). Using possible productivity increases due to higher levels of atmospheric carbon, as well as increased release of carbon through faster decomposition under warmer temperatures and decreased productivity due to environmental stress, they estimated potential carbon gains and losses. In making these estimates, they assumed that 45% of phytomass is carbon, and used the top 1 meter of soil for soil estimates. They found that temperate forests have by far the greatest potential to sequester carbon through vegetation growth, while wetlands have the greatest potential to sequester carbon in soils (see table 2).

Table 2: Global potential annual carbon sequestration in terrestrial ecosystems under altered climate regimes($g\ m^{-2}/y$) (Amthor and Huston 1998)

Ecosystem Type	Potential Carbon Sequestration in Soils ($g\ m^{-2}/y$)	Potential Carbon Sequestration in Vegetation ($g\ m^{-2}/y$)	Total Potential Carbon Sequestration ($g\ m^{-2}/y$)
Temperate Forest	12,000	122,270	134,270
Temperate Grasslands	23,600	720	24,320
Wetlands	72,000	4,300	76,300
Woodlands (slightly less dense than forest)	12,000	8,000	20,000

These numbers vary significantly from those presented by Watson et al (2000) because they represent the amount of carbon that could be sequestered annually under altered climate regimes, not the amount already present in terrestrial ecosystems.

It is important to note two key limitations of this model. First, Amthor and Huston (1998) intended these numbers to act as a framework for planners and scientists to help direct research and protection efforts. These estimates are only semi-quantitative predictions and are not based on empirical measurements. One key difference between these estimates and the actual response of ecosystems may include the way soil organic carbon levels change in response to increased carbon as this can be impacted by factors such as prior land use, species selection, and percent clay in the soil (Laganiere *et al.* 2010).

The second limitation is that these are modeled estimates of carbon accrual based on global-scale, generalized ecosystems classified by climate and major flora and fauna. This has two major implications for applying estimates to finer-scale patches such as residential developments. First, the model assumes mature, undisturbed ecosystems, but in reality there are variations in carbon sequestration rates between young and old woody vegetation, and variations in how disturbed soils may accrue carbon. Second, the model assumes homogeneous vegetation cover. In fragmented and spatially heterogeneous land cover, such as residential neighborhoods that include remnant patches of tree cover, the landscape may respond to elevated carbon dioxide levels and altered climate differently from a homogeneous wildland patch of vegetation in the same soil and climate.

Human decision-making, design and carbon sequestration

Because of their clearly demonstrated ability to store and sequester carbon, maintaining and restoring ecosystems such as forests, prairies and wetlands will help to mitigate climate change, and might be counted as carbon offsets in emerging carbon markets. This suggests an opportunity to maximize the co-benefits of carbon offset projects by also treating them as large-scale ecological restoration projects. In 2009, Galatowitsch proposed that in order to ensure that the carbon markets allow the latitude to pursue maximization of ecological co-benefits, emerging markets must follow three key recommendations: they must develop social and environmental impact assessment tools, they must adopt carbon accounting practices that allow for natural disturbance regimes; and they must improve additionality and leakage testing to prevent loss of carbon storage elsewhere. For this paper, the important message from these recommendations is that, when making choices that will increase carbon storage on a site, designers should also take into account the impacts of those choices on other ecosystem services. They should also consider additionality of carbon storage as compared with existing land cover, and the off-site impacts of any project, including effects on carbon cycling elsewhere (Galatowitsch 2009).

In planning for mitigating climate change, designers and planners are also presented with the opportunity to enhance an ecosystem's capacity to adapt to changing local climates. By serving as connections between and enhancements to the size and composition of existing biological reserves, carbon offset projects can protect existing reserves, buffer against changing weather patterns, and facilitate the natural migration of species, including those that are rare and endangered, into new home ranges as the climate shifts. Furthermore, land managers can encourage higher biodiversity and age heterogeneity among plant species in order to increase stand resilience (Galatowitsch *et al.* 2009).

Carbon sequestration and storage in forest biomass

Reforestation is an obvious way to sequester carbon and may simultaneously serve other ecosystem functions including increasing plant and animal biodiversity and slowing runoff rates (Kim *et al.* 2008). In a study conducted in western Australia, Harper et al. (2007) calculated the average above ground carbon stock in a forest after a 20 year period, then found the difference between this mean and the above-ground carbon stock on agricultural land. They found that if only 16.8 Mha of cleared farmland were reforested, 2200 Mt CO_2 might be sequestered in above ground biomass as the forest matured (Harper *et al.* 2007). This study did not take into account below ground biomass or carbon storage in soils, but as suggested by Amthor and Huston (1998), the amount of carbon stored below ground in forests may be significantly smaller than the amount stored in above ground biomass.

The assertion that a large proportion of carbon in forests is stored in above ground biomass is also supported by a study conducted from on previously cultivated soils in South Carolina. Richter et al (1999) found that 80% of the total carbon newly sequestered in secondary growth forests is in above ground biomass (Richter *et al.* 1999). The previously farmed land was planted with loblolly pines (*Pinus taeda*) in 1957; in 1997, 80% of newly accumulated carbon was found in trees, 2% was in forest floor litter, and 1% was in mineral soils.

It is important to note, however, that soil sequestration rates are likely to be affected by characteristics such as percent clay content and previous land use (Laganiere *et al.* 2010). In the South Carolina site, low mineral soil sequestration rates can be attributed to course soil texture and low activity clay mineralogy, both of which lead to a low carbon sequestration potential. Furthermore, the humid, wet climate causes rapid organic matter decomposition. While soil organic carbon recovery on reforested land is poorly understood, it varies greatly based on local site conditions (Laganiere *et al.* 2010).

Another soil characteristic that will impact the amount of carbon sequestered in plant biomass is nitrogen level. The amount of carbon taken up through new plant growth exceeds carbon losses through microbial decomposition, particularly in young forests with high growth potential and in forests with increased levels of nitrogen. In fact, increased nitrogen can increase the amount of carbon sequestered by terrestrial vegetation by 100-1300 Tg per year (Vitousek *et al.* 1997). In a study conducted by Oren et al (2001), *Pinus taeda* in nutrient poor soils experienced undetectable increases in average biomass carbon over a two-year growth period. For the same species with moderate nutrient levels, biomass carbon accrual stabilized at a marginal gain after three years. When the same species was exposed to both elevated carbon dioxide levels and nutrient rich soils, a large synergistic gain in biomass carbon was detected over the two-year growth period. This study clearly illustrates the need to consider soil fertility in planning for carbon sequestration (Oren *et al.* 2001). In residential developments, lands that house large amounts of nitrogen due to natural soil chemistry or history of agriculture, or lands that fall in the drainage path for nitrogen rich agricultural runoff may be better suited to act as carbon sinks through reforestation compared with less nutrient rich sites.

This does not imply, however, that all soils need to be fertilized or have augmented nitrogen levels to effectively store carbon. In suburban and urban watersheds, natural nitrogen production far outweighs the input of fertilizers in residential lawns and on food crops. In areas where nitrogen application is quite high, such as residential neighborhoods downstream of agricultural land or in fertilized lawns, nitrogen levels in the soil may be controlled by a combination of natural soil process and human inputs (Groffman *et al.* 2006). While nitrogen may be a limiting factor to carbon storage in some landscapes, it is certainly not in all, and land managers should consider this when considering applying additional nitrogen.

The vertical structure, stand age and species of tree selected for a reforestation project will also have a large impact on carbon storage. A study conducted by Turner et al (2005) compared six residential lots in Toronto, Canada with four forested plots that represented the dominant conifer forest ecosystem prior to construction of the residential neighborhood. They found that while residential yards tend to be more biodiverse than the forested plots due to the selection of species by homeowners, the yards are dominated by invasive species, and have woody vegetation with smaller basal areas than those found in native species forested plots. Therefore, holding area constant, less carbon was stored in the vegetation in the Toronto yards than in a naturalized area. Furthermore, due to the larger surface area of their root systems, the native forest plots may sequester additional carbon as compared to the residential areas (Turner *et al.* 2005).

In addition to selecting native species, ensuring a mix of fast growing pioneer species and slower-growing hardwood species may further enhance carbon sequestration in forests. Montagnini et al (2004) found that in Costa Rica, pioneer species accrue more carbon over the first ten years of reforestation, but that slow growing species may accumulate more carbon in the long term. Furthermore, slow-growing hardwoods are often more valuable as construction timber, furniture or woodcrafts and therefore may serve as longer-term sinks for fixed carbon. In addition to recommending species composition, Montagnini et al also found that greater density stands also sequester more carbon, a factor that can be taken into account in forest patch restoration and design (Nair *et al.* 2009). It is important to note that this study was conducted in the tropics, and that results may vary in temperate biomes.

Carbon sequestration and storage in soils

Although in forest ecosystems trees are the largest contributor to carbon sequestration in the short term, if all ecosystem types are considered together, soils store 4 times the carbon in terrestrial vegetation (Delgado and Follett 2002). Soil carbon is stored in two major pools: soil organic carbon (SOC) and soil inorganic carbon (SIC); combined, these two pools contain 3.2 times the carbon in the atmosphere (Delgado and Follett 2002). SIC does not change based on management or land use decisions, so SOC is more relevant for this work. Because of the substantial carbon pool present in SOC, soil management is particularly important to sequestering carbon and keeping it in place.

Unlike vegetation growth, the role of soil in carbon sequestration will be negligibly impacted by rising temperatures and atmospheric carbon levels as long as land cover is not drastically altered by natural disaster (Sindhøj *et al.* 2006). However, disruption of soils and development can change the way that soils process and store carbon. As an area becomes more urbanized, shifts occur in soil chemistry, temperature regimes, soil community composition and nitrogen carbon fluxes (Pouyat *et al.* 2002). These changes may extend beyond the property boundaries of the development site and affect nearby forested ecosystems that are not directly or physically disturbed (Pouyat *et al.* 2002). A study conducted by Jabro et al (2008), which compared no tillage, conventional tillage conducted with a rototiller to a depth of 10 cm and continuous vegetation with alfalfa and grasses, confirms that soil disruption may release soil carbon. They found that minimizing tillage during conversion of land from perennial forages to annual crops can minimize evolution of carbon from soil stores to atmospheric carbon (Jabro *et al.* 2008). Applying these same concepts to residential developments, disrupting soil during construction should be minimized as much as possible in order to reduce the amount of soil carbon that is converted to carbon dioxide and minimize negative impacts on nearby forest soils.

If soil disruption has already occurred, planting native perennial grasses can help to increase soil carbon. A study conducted by Baer et al (2000) found that for property enrolled in the Conservation Reserve Program (CRP), lands converted from agriculture to native perennial grassland for ten growing seasons showed carbon increases of 141% in the active microbial pools, but little increase in overall carbon (Baer 2000). Baer found little difference in total soil carbon levels between land with short tem (zero growing seasons) enrollment in the CRP and long term (ten growing season) enrollment, meaning significantly more than 10 years may be necessary to bring soil to pre-cultivation carbon levels in native prairies (Baer 2000).

However, a study conducted by Simmons et al (2008) compared three areas in West Virginia: a native forest ecosystem, a clear cut but not mined watershed, and a clear cut and surface mined watershed. They found that when the mined watershed was replanted with non-native pasture grasses, the soil mineral horizon carbon pool was equal to 96% of that found in the native forest ecosystem after only 15 years, and the total below ground carbon equaled 73% of that found in the forest ecosystem (Simmons *et al.* 2008). They hypothesized that this rapid increase in total soil carbon was likely due to litter inputs and below ground root activity of the grasses.

An empirical study conducted by Kurganova et al (2008) suggests that the amount of carbon sequestered in soils declines after the first 15 years. This study, conducted near Moscow on several fields converted from agriculture to grassland found that in the first 15 years, soils sequestered 132+-21 g C m_{-2} yr_{-1}, but only sequestered 70+- 8 g C m_{-2} yr_{-1} in years 15-30. The also found that soils in dry climates sequestered significantly less carbon than those in wetter climates (Kurganova *et al.* 2008). As the results of the Kurganova et al study suggest, it may take soils significantly longer than 15 years to return to pre-disturbance carbon levels. In fact, Knops et al (2000) determined that it would take 230 years for soil carbon to return to pre-agricultural levels by using a dynamic model fitted to the carbon levels observed in 1900 abandoned agricultural fields in a Minnesota sand plain over 12 years (Knops and Tilman 2000).

The variation in research results regarding SOC regeneration likely relates to differences in historic land use patterns and soil disruption, species selection, and soil texture and clay content. A meta-analysis conducted by Laganiere et al (2010) found that in general, soils will show faster carbon recovery after reforestation if they were previously agricultural rather than pasture or natural grassland, had minimal prior disturbance, and have a high clay content (Laganiere *et al.* 2010). While this analysis looked only at the impacts of reforestation on SOC, similar variation in SOC accumulation based on local conditions such as soil composition and management choices including species selection likely exists under different re-vegetation regimes as well.

The herbaceous species selected for revegetation on disturbed lands will affect the amount of carbon sequestered in soils, as well as the rate of sequestration. A study conducted by Steinbeiss et al (2008) looked at managed grasslands on former agricultural fields, and found that in these newly planted grasslands, carbon storage was limited to the top 5 cm of soil, and that below 10 cm carbon was actually lost, most likely due to soil disruption during land-use change. After four years, however, these same grasslands showed significant increases in carbon storage within the top 20 cm, and soil carbon losses significantly decreased. They hypothesize that this increase in carbon storage across soil horizons depths reflects an increase in sown species richness. The large root biomass of grassland plantings encourages carbon storage, but Steinbeiss et al concluded that the overall increase in carbon storage can be more directly linked to an increase in plant biodiversity as a whole. Including tall herbs in a biodiverse plant mix is particularly important for reducing carbon losses below 20 cm in a new grassland scenario (Steinbeiss *et al.* 2008).

A study conducted by Fornara and Tillman (2008) at the University of Minnesota further supports the assertion that increasing species richness in newly planted grasslands will increase carbon sequestration rates over time. Fornara and Tillman compared carbon sequestration rates in a biodiverse grassland verses a monoculture plot over 12 years. They found that the biodiverse grasslands had higher soil carbon sequestration rates of 0.72 ± 0.08 Mg ha_{-1} yr_{-1} as compared to the monoculture plots. They also found that the presence of legumes and C4 grasses in the biodiverse plots increased soil carbon sequestration rates over 12 years by 180% and 363% respectively (Fornara and Tilman 2008). Both the Fornara et al and Steinbess et al studies support the assertion that increasing biodiversity and including legumes and C4 grasses in residential grasslands will lead to an increase in carbon sequestration.

In areas of the lawn that are maintained as grassland, other planting bed or lawn, management practices will have a large impact on carbon storage. Practices that will increase soil carbon sequestration include keeping deep soils moist to promote deep rooting, allowing plant residue to decompose in place, and using natural fertilizers to make up for nutrient deficiencies where necessary. Milesi et al (2005) conducted a study of lawns planted with grasses that require both cool and warm seasons to thrive in residential settings across the contiguous 48 states. Study transects extended from urban cores to suburban fringes in 12 cities across the U.S.. Using the Biome-BGC ecosystem process model, they found that those sections of the yard maintained as lawn act as carbon sinks when they are well fertilized and watered. They asserted that reaching the correct level of irrigation would require 695-900 liters of water per person per day. Water usage at this level may be beyond a sustainable level, so homeowners should plant grass species that require less water and utilize technologies that capture and recycle waste and storm water (Milesi and Running 2005).

It is key to note, however, that the way lawn is managed can create life-cycle carbon emissions that outweigh turf grass and soil carbon sequestration. According to a study conducted by Townsend-Small and Czimczick (2010) in four parks near Irvine, California, the global warming potential (GWP) caused by carbon emissions from fertilizer production, mowing, leaf blowing and other management practices, as well as the nitrous oxide emissions from fertilization, is greater than the GWP offset by carbon sequestration in ornamental lawns (Lombardi 2010). Lawn will only sequester enough carbon to offset carbon and nitrous oxide emissions and assist in climate change mitigation if management practices that emit greenhouse gasses, like using fuel consuming mowers and leaf blowers and applying manufactured synthetic fertilizers, are avoided.

Allowing plant residue to decompose in place is one low energy input way to increase soil carbon sequestration, leading to an overall increase in soil organic carbon and soil water retention. Duiker et al (1999) conducted a study comparing the impacts of crop residue on test plots on a farm in central Ohio. They found that over seven years, crop residue application increased soil organic content and soil water retention in the top 10 cm of soil, particularly in ridge till and no till systems. The increase in soil water retention was attributed to an increase in the number of soil macropores with a diameter of 1 to 10 um (Duiker and Lal 1999). Similarly, in a study that utilized 67 global long-term agricultural experiments, West et al (2002) found that changing from conventional to no till management can sequester 57+/-14 g C m-2 on average annually, peaking after five to ten years and reaching a new carbon equilibrium after fifteen to twenty years (West and Post 2002).

Applying the same concept of returning plant residue to the soil in a residential system, Qian et al (2003) used the CENTURY ecosystem model to determine the impacts of returning Kentucky Bluegrass clippings to turf instead of removing them. They found that over 10-50 years on clay loam soils in Colorado, soil carbon sequestration would increase by 11 to 25%. Results of this model were then compared against field measured clipping yields for Kentucky Bluegrass (Qian *et al.* 2003). These results along with the Duiker et al, and West et al, and Milesi et al studies suggest that allowing plant residue to decompose on site instead of removing it may lead to an increase in soil water retention, and therefore increased carbon sequestration.

Finally, using natural fertilizers, like poultry litter, may increase soil carbon sequestration without releasing the greenhouse gases associated with synthetic fertilizer production. A study conducted by Sainju et al (2008) found that on test plots in northern Alabama over a 10 year period, applying poultry litter led to soil carbon sequestration rates of 510 kg C ha_{-1} yr_{-1} annually, where as conventional NH_4NO_3 fertilizer only sequestered –120 to 147 kg C ha_{-1} yr_{-1} annually. Poultry litter also increased potential carbon mineralization rates and microbial biomass carbon (Sainju *et al.* 2008). In the context of soil management in residential sites, this implies that using natural fertilizers in place of synthetic ones over the long term (>9 years) can lead to an overall increase in soil carbon sequestration due to an increase in overall soil quality. Also, according to an estimate based on the Carnegie-Mellon Economic Input-Output Life Cycle Assessment, utilizing natural fertilizers and pesticides instead of their synthetic counterparts will accrue $16-$21 of environmental benefits per U.S. household including reduced negative impacts on human health and increased ecosystem function (Morris and Bagby 2008).

Chapter III

Planning and Design Guidelines Based on the Literature Review

Preserve existing ecosystems where ever possible, especially wetlands, prairies and forests

Maximize co-benefits, including habitat and ecosystem recovery, when planning for carbon storage

Create constructed wetlands where soils and conditions are appropriate

Create deep rooting grasslands with C4 grasses and legumes and keep them there

Nitrogen application and increasing carbon sequestration
Increasing soil nitrogen will increase carbon sequestration in soils and biomass where nitrogen is the limiting factor for plant growth (Sainju et al. 2008). However, applying nitrogen beyond the amounts required for optimum plant growth will lead to increased nitrate in runoff and could have devastating ecological impacts. Nitrates are one of the major causes of hypoxia in the Chesapeake Bay and Mississippi River watersheds, and contributes to the growth of dead zones in these waters (Burkart and James 1999). Soil testing will identify if soil nitrogen levels are deficient, and should be performed prior to prescribing nitrogen application.

On land that will be reforested, plant with deep rooting C4 grasses and legumes prior to or together with planting trees

In forests, plant a combination of slow growing and pioneer tree species. Allow forested areas to naturalize, and select native species where possible to increase co-benefits

Avoid disturbing soils

When planting perennials, aim for high biodiversity, and include deep rooting herbs, legumes and C4 grasses

In lawn and planting beds, keep deep soils moist by using water conservation practices like rain gardens, retention ponds, and rain barrels. The amount of watering desirable depends on regional climate and soil conditions

Allow plant material, including grass clippings, leaves, and perennial and annual plants to decompose on site and be incorporated into soil

Modeling Carbon Storage
COLE Model The COLE model utilizes the USDA Forest Service Inventory and Analysis from different areas around the US to determine tons of carbon per hectare. The model calculates quantitative variables including total tree carbon, forest carbon, dead trees, live trees, understory vegetation, dead wood, and forest floor and soil organic carbon (USDA and National Council for Air and Stream Improvement). Users can then select categorical variables that sort the quantitative values. These variables include state, county, owner, owner group, forest type and group, stand size, productivity class, measurement year, stand age, reservation status, and stand origin land clearing status (USDA and National Council for Air and Stream Improvement). This model is helpful where individual estimates of tree size and species are not feasible. However, the COLE model is most accurate when used for areas of a county or larger, and the uncertainty of the carbon estimate decreases as land area increase (USDA 2009).
The CTCC Model The CUFR Tree Carbon Calculator (CTCC) uses an excel spreadsheet to calculate carbon storage information for a single tree including the amount of carbon dioxide stored in a tree over several years and the past year, and dry weight of the above ground biomass. It uses sample growth data from 650-1000 street trees representing 20 common urban tree species to estimate carbon storage (Mcpherson *et al.* 2009). To obtain carbon storage values for these species, biomass equations were developed for each species. These equations were often derived from volumetric measures of city trees. Tree species vary by region selected. For the Midwest region (region 12), these species include: *Acer negundo, Acer platanoides, Acer rubrun, Acer saccharinum, Acer saccharum, Celtis occidentalis, Fraxinus americana, Fraxinus pennsylvanica, Ginkgo biloba, Gleditsia triacanthos, Ilex opaca, Malus sp., Magnolia grandiflora, Pinus contorta var bolanderi, Pinus nigra, Pinus ponderosa, Quercus nigra, Quercus palustris, Quercus rubra, Tilia americana, Tilia cordata, Ulmus americana* and *Ulmus pumila*. CTCC can also be used to calculate energy savings from tree shading including annual savings in kilowatt-hours of electricity and MBtu of heating, and the carbon dioxide

equivalents of these savings. In order to obtain these values, users must input information on specific tree sizes, ages, and species, as well as the climate region in which they are located (Mcpherson *et al.* 2009). This model can calculate fairly accurate estimates for a city or regions forest carbon store. However, because this model requires measurement of individual trees, it may be difficult to use for large areas. Furthermore, broad climate regions may not capture the exact conditions of a location, and therefore may not correctly estimate the rate of tree growth, building characteristics, or microclimate (Mcpherson *et al.* 2009). This can be corrected by applying biomass equations manually, but may make this model less accessible to the general public (Mcpherson *et al.* 2009).
i-Tree Streets (formerly STRATUM) The i-Tree Streets program (formerly known as STRATUM) quantifies dollar values for energy conservation, air quality improvement, CO2 reduction, stormwater control and property value increase due to street trees using street tree inventory data (USDA). While it is related to the CTCC model in that both use the same 16 climatic zones, the main difference is that CTCC produces carbon dioxide emission and storage values, while i-Tree Streets monetizes these services. Inputs for this model can be a complete tree inventory, or a sample inventory that only includes 3-6% of the overall street tree canopy (USDA).
The California Climate Action Registry The CTCC model is the only model approved by the California Climate Action Registry for Urban Forest Project Reporting Protocol(Anonymous 2008). This protocol aims to account for greenhouse gas emission reductions performed by tree planting and maintenance on specific site and city scale projects, and includes detailed steps for how to inventory existing trees, calculate potential carbon biomass, and use the CTCC model(Anonymous 2008).

Chapter IV

Case Studies

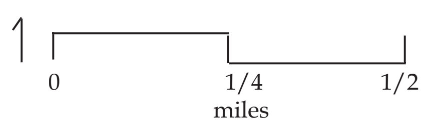
Introduction

The guidelines developed through the literature review will now be applied to the critique of two celebrated conservation subdivisions: Prairie Crossing in Grayslake, Illinois and Coffee Creek in Chesterton, Indiana. This critique serves two purposes. First, it highlights the similarities between current conservation subdivision planning practices and the guidelines proposed in this thesis for carbon sequestration. Second, the analysis of these case studies will emphasize a few key changes to current design and planning practices for conservation subdivisions that could have a large impact on carbon sequestration in exurban residential neighborhoods.

Coffee Creek

Figure 1: Coffee Creek Master Plan

Photo Credit: www.cdfinc.com



In 1996, the Lake Erie Land Company (LEL) acquired nearly 700-acres of land straddling Coffee Creek in Chesterton, Indiana (Arvidson 2004). Jerry Mobley, the president of LEL, envisioned a vibrant mixed-use community with the primary goal of economic development (Arvidson 2004). Upon surveying the property, Mobley was inspired by Coffee Creek, and decided that protecting and restoring of the creek would also be an important aim of the project (Arvidson 2004). The team of consultants hired to work on the project included green architects William McDonough + Partners, botanists and wetland ecologists from JFNew, and the landscape architecture firm Conservation Design Forum (CDF).

Initial site assessment by CDF revealed a wealth of natural resources, including functioning fens and riparian wetlands, as well as a 300 year-old American beech (*Fagus americana)* tree that would later serve as the backbone of restored riparian forests (Barker 2009). The health of the existing ecosystems and the potential for restoration led the development to create a master plan centered on what is today the 167-acre Coffee Creek Watershed Preserve (Arvidson 2004). The preserve includes about 100 acres of forest dominated by American beech, sugar maple (*Acer saccharinum)*, Oak (*Quercus spp.)* and Hickory (*Carya spp.)* and just over 50 acres of open prairie and wetland (Barker 2009).

The original Coffee Creek plan called for 3,000 housing units and 4 million square feet of commercial space (Arvidson 2004). As of 2000, the average cost of a residential unit in the development was $140,000 (Klucas 2000). Unfortunately, sales in the property have been slower than expected, perhaps due to the stringent permitting process that LEL's Kevin Warren suspects deters many potential developers (Arvidson 2004). As of 2004, only 17 homes had been purchased out of the 250 expected during phase one development (Arvidson 2004).

Analysis for carbon sequestration and storage

- Approximately 100 acres of riparian forest were restored. Forest types include beech/sugar maple and oak/hickory, and are centered on preserved mature trees(Barker 2009). To further optimize carbon sequestration, forest should be managed to include pioneer and slow growing species, as well as a wide diversity of tree ages. Because of the scale of this forest, the COLE model would be an inaccurate tool for measuring carbon storage. In this case, the CTCC model will yield more accurate results, although there are two main limitations to using the CTCC model to calculate carbon storage. First, we lack accurate tree counts for each individual species. Second, the CTCC model does not include any beech or hickory species, dominant trees in this forest.

- In order to estimate carbon stored in this forest, we made four key assumptions. First we assumed that 25% of the 100 acre forest is primarily composed of each dominant tree type. In order to translate this acreage into numbers of each species, we made a second assumption and borrowed the number of trees per acre from a study by the Forest Service that tracked a secondary growth forest at the Alleghany Experiment Station (Anonymous 2006). In this case, they found 346 trees per acre. The third assumption is that trees in the same family will have similar carbon storage values. Therefore, to calculate carbon storage in beech we will be using trees that are included in the CTCC model for the Midwest region, and are from the same family (Juglandaceae for hickory, and Fagaceae for beech trees) as the dominant tree types not included in the CTCC model. Finally, we made the assumption that trees with similar growth rate and density will store similar amounts of carbon. Therefore, if no species from the same family are included in the model, as is the case with Shagbark Hickory, than a species with similar growth habits will be used. All trees were entered with a 6″ diameter at breast height

Table 3: Carbon stored in restored forest of Coffee Creek

Common Name of Dominant Species	**Scientific Name of Dominant Species**	**Substitution species used**	**Total carbon sequestered (kg/tree/year)**	**Total carbon pool size in tree cover (kg/tree)**	**Total carbon sequestered per year in tree cover per 25 acres (kg/year)**	**Total carbon pool size in tree cover per year per 25 acres (kg)**
American Beech	*Fagus americana*	*Quercus rubra*	40.6	172.3	351,190.0	1,490,395.0
Sugar Maple	*Acer saccharum*	_	67.7	370.8	585,605.0	3,207,420.0
Shagbark Hickory	*Carya ovata*	*Quercus rubra*	40.6	172.3	351,190.0	1,490,395.0
Red Oak	*Quercus rubra*	_	40.6	172.3	351,190.0	1,490,395.0
Total carbon sequestered per year and carbon pool size in tree cover					1,639,175	7,678,605.0

- About 51 acres of open prairie was restored on land that was previously agriculture. This planting is entering its tenth year, and is gaining diversity through prescribed burns occurring every 1-5 years. Species include warm season C4 grasses, as well as a diversity of mesic and dry prairie species (Barker 2009). Although reaching pre-agricultural carbon levels in the soil will take time, the diversity of the grasses and the presence of deep rooting herbs including C4 grasses are likely increasing the amount of carbon stored in the prairie.

- Plans to restore a 30-acre wetland will further enhance carbon sequestration (Barker 2009).

- In the preserve, stormwater is managed using a variety of technologies, including porous pavement, infiltration based dry wells, and level spreaders

(Patchett 2009). Keeping soils moist is most likely enhancing carbon sequestration in the preserve.

- The land that now houses the Coffee Creek Development was previously in agriculture. This means much of the native soil profile was already disrupted, releasing carbon stored as soil organic carbon. Despite this previous destruction, soil disruption was minimized during early home construction by avoiding mass grading (Patchett 2009). The current land manager, Steve Barker, is working with current developers and Chesterton's MS4 program to ensure that grading is minimized in new construction as well (Barker 2009).

- Homeowners are encouraged through dissemination of information to minimize traditional lawns by using native and non-native plantings. Many of the new developments, including a section called the Conservancy Neighborhood, have small lots and almost no turf (Barker 2009). Encouraging alternatives to lawns will increase diversity and biomass in yards, and enhance carbon sequestration. Encouraging no-till management of annual flowerbeds and returning grass clippings and leaves to the soil will further increase soil organic carbon.

- Many of the early single-family homeowners in the development chose to have conventional lawns, and because water conservation techniques such as rain barrels were not put into effect, these lawns are most likely only serving as carbon sinks if they are conventionally watered. Some new parts of the development, like the townhouses, include level spreaders and space to incorporate rain barrels (Barker 2009). Helping homeowners develop ways to keep yards watered using storm water will enhance carbon sequestration and lessen the impact of large storm events on Coffee Creek.

Prairie Crossing

Figure 2: Prairie Crossing Master Plan

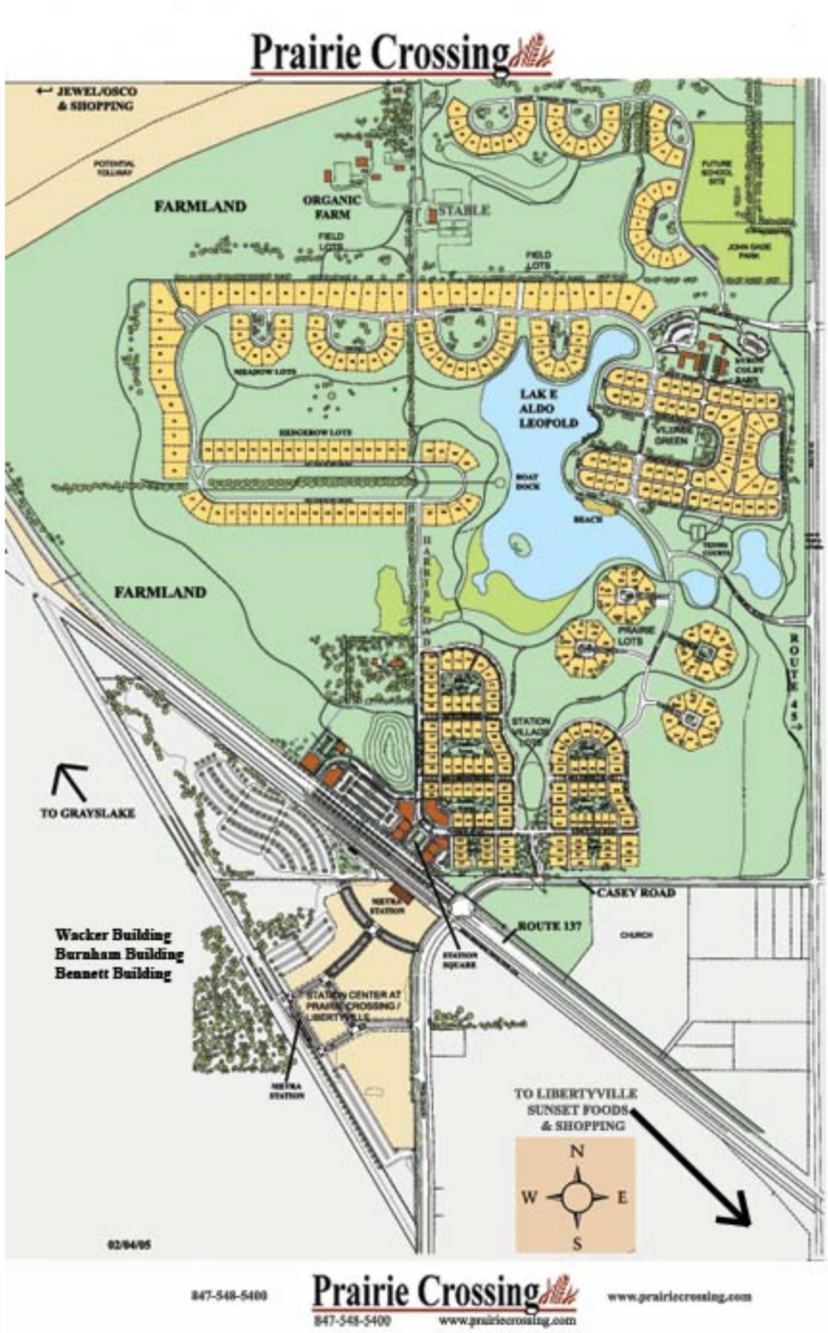
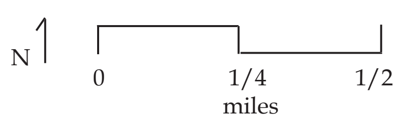


Photo Credit: www.prairiecrossing.com



Prairie Crossing, located about 40 miles northwest of Chicago, Illinois, is a 678-acre development that includes 359 single family homes, 36 condos, and 470 acres of preserved open space (Ranney 2009). When the formerly agricultural site was acquired in 1986, developer Gaylord Donnelley, who passed away in 1992, envisioned a residential community deeply connected to the lands agrarian roots (Martin 1995). Focus groups, however, showed that potential residents feared that living among farm fields meant eventually living among new subdivisions (Martin 1995).

Donnelley's nephew George A. Ranney, Jr., his wife Victoria Post Ranney, a landscape historian, and project leader William Johnson, FASLA, worked together to create a place that respected the natural topography and history of the site. Eventually, the residential development was designed around ten basic principles, including economic development, environmental protection and energy conservation (Dunlap 1999).

Today, the community is centered around the 470 acres of open space, which is made up of primarily restored prairie, but also houses constructed wetlands, preserved hedge rows of osage orange (*Maclura pomifera)* and sugar maple, a chain of small lakes, and a 100-acre organic farm that echoes the properties agrarian roots (Ranney 2009). Currently, all of the single-family homes, with a median price of over $500,000 (Association 2009) are occupied, but this is true for only about 50% of the condominiums (Ranney 2009) highlighting a failure to attract economic diversity to the community (Dunlap, 1999).

Analysis for carbon sequestration and storage

- The property had very few trees when it was acquired for development, but approximately 18 acres of hedgerows were preserved. Species in these hedgerows include oaks, osage orange, northern hackberry (*Celtis occidentalis)*, black cherry (*Prunus serotina)*, sassafras (*Sassafras albidium)*, and sugar maple (Sands 2009). Preserving existing trees helps to maintain carbon stored both in the plant biomass, and in the soil profile beneath them. Because of the scale of this forest, and the species composition that does not represent a dominant forest type, the COLE model would be an inaccurate tool for measuring carbon storage. The CTCC model is also inaccurate as osage orange, black cherry and sassafras are not included in the approximately 20 urban tree species included for the Midwest in the model. Furthermore, so much of the subdivision is preserved in prairie, but the CTCC model is not equipped to calculate carbon storage in ecosystems other than forests, and therefore will not accurately represent the amount of carbon stored in Prairie Crossing. We used the same four assumptions when utilizing the CTCC model to calculate carbon storage for the Coffee Creek case study. In this case, we assumed that all tree species are present in equal proportion on the 18 acres (3.6 acres per tree species).

Table 4: Carbon stored in preserved hedgerows of Prairie Crossing

Common Name of Dominant Species	**Scientific Name of Dominant Species**	**Substitution species used**	**Total carbon sequestered (kg/tree /year)**	**Total carbon pool size in tree cover (kg/tree)**	**Total carbon sequestered per year in tree cover per 3.6 acres (kg/year)**	**Total carbon pool size in tree cover per year per 3.6 acres (kg)**
Oaks	*Quercus spp.*	*Quercus rubra*	40.6	172.3	50,571.4	214,616.9
Osage Orange	*Maclura pomifera*	*Malus spp.*	27.6	153.1	34,378.6	190,701.4
Northern Hackberry	*Celtis occidentalis*	-	79.7	343.2	99,274.3	427,489.0
Black Cherry	*Prunus serotina*	*Malus spp.*	27.6	153.1	34,378.6	190,701.4
Sassafras	*Sassafras albidium*	*Malus spp.*	27.6	153.1	34,378.6	190,701.4
Total carbon sequestered per year and carbon pool size in tree cover					252,981.5	1,214,210.1

- Street trees include northern hackberry, swamp white oak (*Q. alba)*, chinkapin oak (*Q. muhlenbergii)*, bur oak (*Q. macrocarpa)*, catalpa (*Catalpa speciosa)* , musclewood (*Carpinus caroliniana)*, and green ash (*Fraxinus pennsylvanica)*.

Unfortunately, street tree planting was only included in the last phases of development, so the majority of trees were not installed until 2004. To date, 288 street trees have been planted in the single family residential phase of the development, called Station Village (Sands 2009). The combination of faster growing species, such as catalpa, and slow growing species, such as oaks will help to enhance carbon sequestration now and in the future. Again, even with on the ground measurements of each of these trees, the CTCC model would not be an adequate tool for measuring carbon storage, as many of the species planted as street trees in Prairie Crossing are not included in the CTCC model.

- In the lower density residential areas, surface bioswales capture storm water from each property and channel it to a 30-acre constructed wetland. In higher density areas, storm water is captured by a conventional underground system that later daylights into the bioswale system (Ranney 2009). Allowing storm water to infiltrate increases soil moisture and aids in plant growth. Therefore, it may increase the amount of carbon sequestered by soils and vegetation.

- 175 acres were restored to prairie in 1994 with dominant C4 grasses such as big bluestem (*Andropogon geradii)* and indian grass (*Sorghastrum nutans)*. Diversity of the plot is further enhanced by forbes such as blazing star (*Liatris spicata)*, coneflower (*Echinacea purpurea)* and silphiums (*Ferula spp.)* (Sands 2009). Although 15 years is likely not long enough to rebuild the historic soil profile on previously agricultural land, the diversity of the plot, and particularly the presence of deep rooting, C4 grasses may increase the amount of carbon stored in the prairie soils.

- Homeowners maintain their own properties, and were given a choice between two different yard treatments: a conventional lawn, or a yard planted with a variety of native prairie species. Adoption of the native lawn was encouraged through incentives, including increased spending by the developer on plant materials and consultation with a landscape architect. Early residents were quick to choose the native plant option, but a second wave of home buyers, perhaps deterred by the messy appearance of their neighbor's fledgling prairies, chose primarily conventional. Adoption of the native yard has remained cyclical, but has increased in recent years (Ranney 2009). Today, on the smaller village lots where homes are situated just a few feet from the sidewalk, the majority of homeowners still choose conventional lawn. In the larger lots, 65-70% of homeowners have adopted the native lawn (Sands 2009). While allowing storm water to infiltrate may help conventional lawns maintain sufficient moisture and therefore act as carbon sinks, the native lawns have higher biodiversity and deep rooting C4 plants, and may be sequestering more carbon in soils.

- Sections of the 100-acre organic farm are tilled each year, but plant matter is incorporated into the soil after each season (Sands 2009). Tillage is most likely disrupting the soil and allowing for carbon release. However, decomposition of plant matter into the soil each season may increase the soil organic carbon stores.

Chapter V

Subdivision Design

Site background

We applied these guidelines to an approximately 39-acre subdivision site on the outskirts of a post-industrial city with a shrinking population in the state of Michigan in the northern Midwest of the United States. After clearing about one third of the land on the site in 2002, developers built three of the projected 105 houses and about one third of the road system before going bankrupt. No further construction took place on the site, sparing the remaining forest which would have been nearly all destroyed had the original plans come to fruition (Figure 3). Over time, one of the three constructed homes burnt down, and now only its driveway remains. Residents of the remaining two houses would like to see the site developed into a neighborhood, but told us that they would be satisfied with the installation of sidewalks and street lamps.

Historically, the site is a part of a temperate forest biome and was dominated by American beech and sugar maple. An approximately 17- acre remnant of this forest exists on the eastern side of the site, and is flanked by a housing development to the east, a reservoir to the north, and a golf course to the west (Figure 4). Using the CTCC model and the same assumptions utilized when examining the case studies, this forest remnant has a carbon pool of 1,597,257.1 kg of carbon and sequesters 318,510.3 kg of carbon per year (Table 5).

Table 5: Carbon sequestered and stored in forest on site

Common Name of Dominant Species	**Scientific Name of Dominant Species**	**Substitution species used**	**Total carbon sequestered (kg/tree/year)**	**Total carbon pool size in tree cover (kg/tree)**	**Total carbon sequestered per year in tree cover per 8.5 acres (kg/year)**	**Total carbon pool size in tree cover per year per 8.5 acres (kg)**
American Beech	*Fagus americana*	*Quercus rubra*	40.6	172.3	119,404.6	506,734.3
Sugar Maple	*Acer saccharum*	_	67.7	370.8	199,105.7	1,090,522.8
Total Carbon Sequestered per year and stored:					318.510.3	1,597,257.1

A cursory walk through this forest suggested that it is still heavily dominated by American beech and sugar maple trees. Surprisingly, there was no evidence of invasive species. Early native successional species are moving into the previously cleared western third of the property, and are predominately native tree species such as staghorn sumac (*Rhus typhina*) and quaking aspen (*Populus tremuloides)*, and herbaceous species such as New England aster (*Aster novae-angliae)* and goldenrod (*Solidago spp.)*. The lack of invasive species encroaching on the cleared field supports the assertion that the site has not been heavily impacted by invasive species.

Redevelopment Scenarios

Because the future of this site is unclear, we developed designs at two scales to consider their effects on carbon sequestration and other ecosystem services. First, we developed two different subdivision designs: one based on an ecosystem restoration scenario that assumes no further development, and another based on a conservation subdivision scenario. Then, at the scale of individual yards in the subdivision, we examined how these small sites could be designed to enhance carbon sequestration and other ecosystem services.

For all designs, we used a plant palette that will promote carbon sequestration and storage in plant biomass and soils, as well as support restoration and regeneration of ecosystem function (Table 5). Tree species were selected in order to ensure a combination of quick growing pioneer species and slower growing hardwood species and to enhance the existing ecosystems on site, including the American beech/sugar maple forest and a wet patch located in the center of the western developed block. The prairie species include a biodiverse mix of C4 grasses and legumes that will enhance carbon sequestration and be aesthetically pleasing.

Table 5: Potential plant species

Type of Plant and Intended Location	Potential Species Scientific Name	Potential Species Common Name
Street Trees, Forest Restoration Species	*Acer saccharinum* *Fagus americana* *Acer rubrum*	sugar maple American beech red maple
Lot line Species	*Betula nigra* *Thuja occidentalis* *Amelanchier arborea*	river birch eastern white-cedar serviceberry
Rainwater Woodland Species	*Larix laricina* *Fraxinus nigra* *Pinus strobus* *Betula alleghaniensis* *Acer rubrum*	tamarack black ash white pine yellow birch red maple
Prairie C4 Grass and Legume Species	C4 Grasses: *Schizachyrium scoparium* *Sorghastrum nutans* Legumes: *Amorpha canescens* *Astragalus canadensis* *Chamaechrista fasciculata* *Dalea purpurea* *Dalea candida* *Desmodium canadense* *Lespedeza capitata*	C4 Grasses: little bluestem indian grass Legumes: lead plant canadian milkvetch partridge pea purple prairie clover white prairie clover showy tick trefoil roundhead lespedeza

Figure 3: Site analysis map

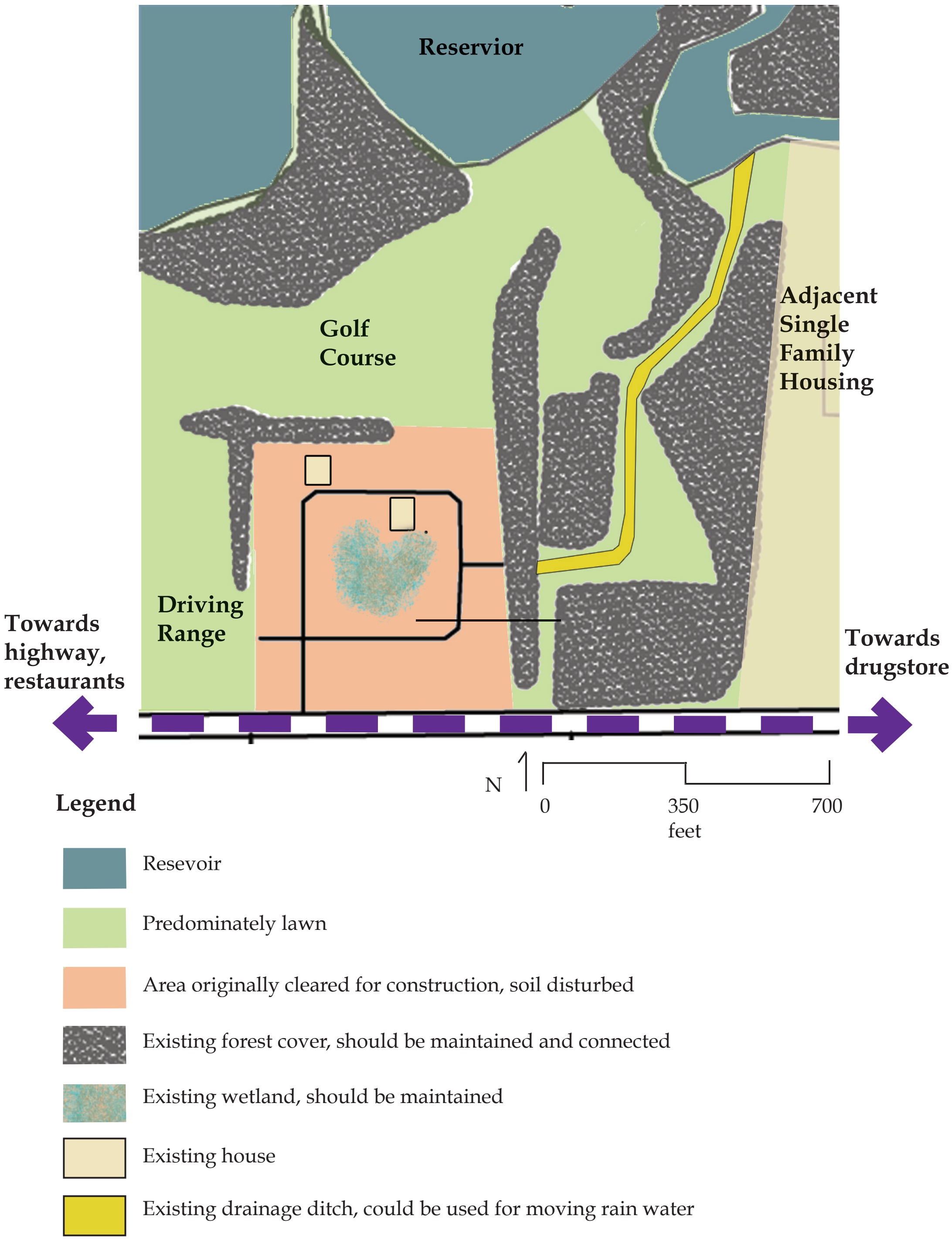
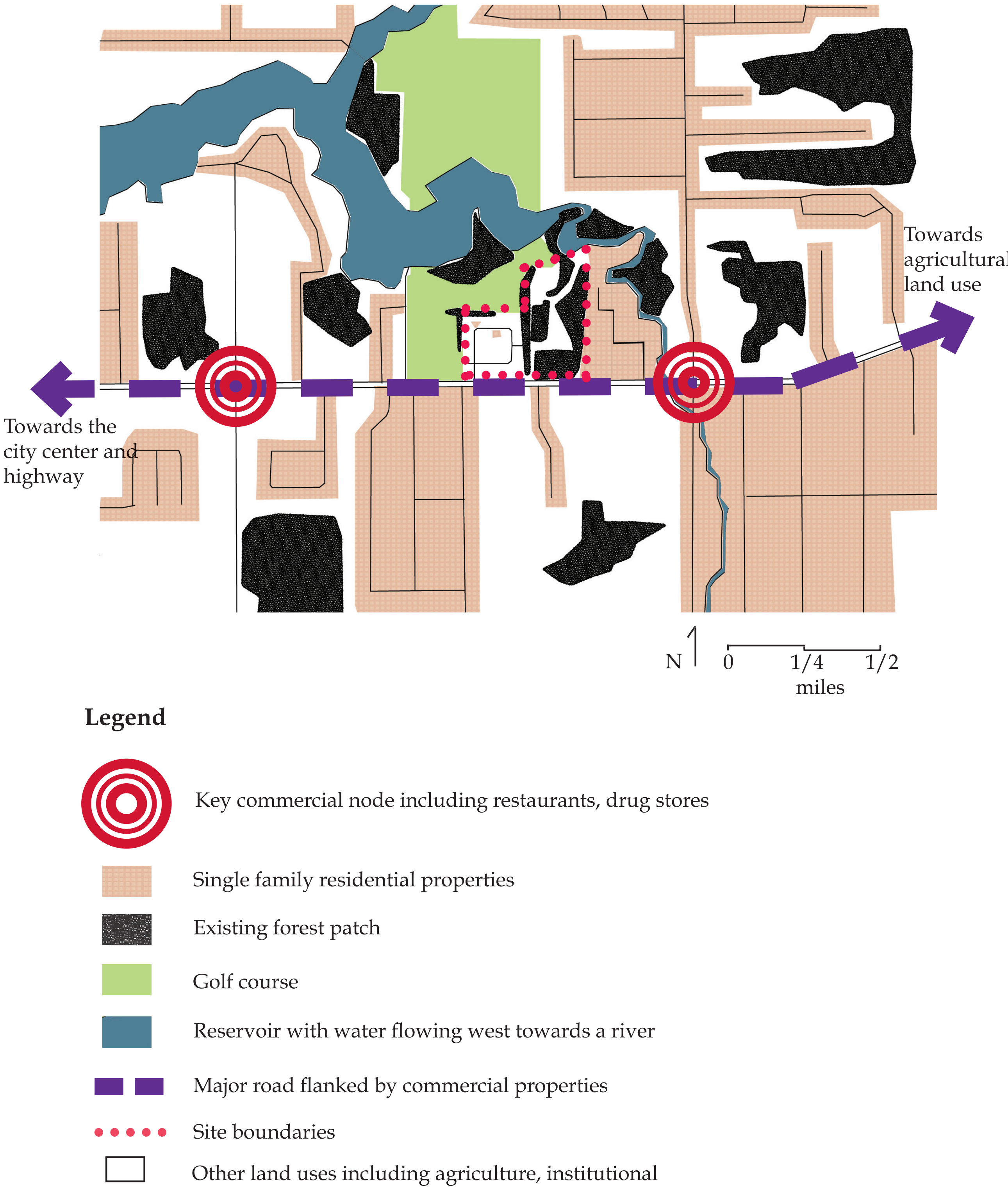


Figure 4: Site context map



The ecosystem restoration design for carbon sequestration

The main goals of the ecosystem restoration design (Figure 5) were to create a neighborhood that is safe and aesthetically pleasing for site residents, appears well maintained, and enhances the ecosystems currently found on the site while enhancing carbon sequestration.

Residents expressed a desire to have a landscape that is easy to maintain as they receive very little support from the municipality. Of particular concern were encroaching quaking aspen trees that have begun to destroy the curb infrastructure on the site (Figure 6). The rapid growth of these aspen trees has also begun to obstruct views around corners, leading residents to fear for the safety of children who often ride bikes around the existing roads.

Figure 6: Quaking Aspen grows through a curb on site

While these native trees are a nuisance to current residents, they are also a part of the natural succession in moist soils like those found in the western block on the site and are a great example of a fast growing pioneer species that will sequester carbon quickly. For this reason, it is important to both cultural and ecological goals of the design to find a way to allow succession to occur while simultaneously preserving infrastructure and enhancing safety for site residents. For this reason, a physical root barrier should be installed at the interface between the mowed edge and the restored rainwater woodland to block the underground rhizomes that allow quaking aspen to rapidly reproduce clonally. This root barrier will help to ensure that the prairie-planted corners of the western block do not become wooded over time, leading to visibility issues. Furthermore, by installing this root barrier, the rainwater woodland can be allowed continue to follow its natural successional patterns as it has been without becoming a threat to safety or infrastructure. Because of the lack of invasive species on the site, and the natural succession occurring with the quaking aspen, this wet soil site should be able to regenerate with minimal human intervention.

The prairie plantings throughout the site should be relatively low maintenance as well, requiring only annual prescribed burns or mowings. The shape of these plantings on block edges and at the entrance of the subdivision, along with the orderly allay of street trees, give the neighborhood the appearance that it is well maintained while simultaneously sequestering carbon in soils. Further prairie plantings on the eastern side of the site will help to increase the carbon sequestered in soils while the newly planted American beech (*Fagus americana)* and sugar maple (*Acer saccharum)* trees begin sequestering and storing carbon in biomass, and eventually fill in to a complete forest canopy.

In order to encourage these trees to fill in and create a relatively closed canopy, they will be planted in strategically placed clumps that close edges of the forest and act as ecological bridges between existing forest patches. In order to decrease cost and increase viability

Figure 7: Seedlings and young trees at the forest edge

by utilizing a local genotype, seedlings and young trees from within the forest can be transplanted (Figure 7). These newly planted links will allow flora and fauna species to move easily between existing patches, and are designed to reach towards one another, encouraging more rapid recolonization of the forest area. Closing the forest edge also serves a cultural function by stopping deer hunters from entering and illegally utilizing the property, an issue residents voiced concerns about. A walking path traces the outer edge of the forest, giving residents a way to interact with the forest without encouraging entry into the forest interior, which could be detrimental to wildlife

After successful restoration, this site will house 28.5 acres of beech/sugar maple forest. Using the CTCC model, and the same assumptions utilized when examining the case studies, this forest patch will have a carbon pool of 2,677,754.5 kg, and sequester 533,973.1 kg of carbon per year (Table 7).

Table 6: Carbon sequestered and stored in forest on site under the completed restoration plan

Common Name of Dominant Species	Scientific Name of Dominant Species	Substitution species used	Total carbon sequestered (kg/tree/ year)	Total carbon pool size in tree cover (kg/tree)	Total carbon sequestered per year in tree cover per 14.25 acres (kg/year)	Total carbon pool size in tree cover per year per 14.25 acres (kg)
American Beech	*Fagus americana*	*Quercus rubra*	40.6	172.3	200,178.3	849,525.1
Sugar Maple	*Acer saccharum*	_	67.7	370.8	333,794.8	1,828,229.4
Total Carbon Sequestered per year and stored:					533,973.1	2,677,754.5

Figure 5: Ecosystem restoration design

N 0 100 200
feet

Legend

Beech/sugar maple tree species

Rainwater woodland

Eco-lawn turf

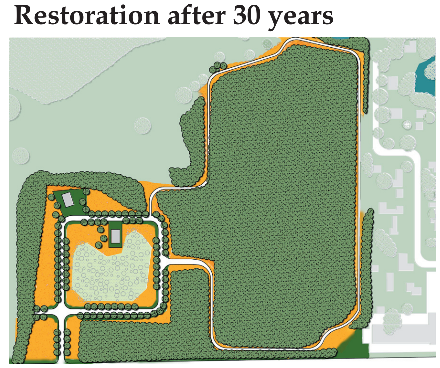
Single family residential home

Prairie plantings with C4 grasses and legumes

Trees to be planted

------- Existing drainage ditch

Restoration after 30 years



The conservation subdivision design for carbon sequestration

The goal of the conservation subdivision design is to create a desirable, culturally sustainable neighborhood while simultaneously maximizing carbon sequestration and co-benefits such as stormwater management and habitat creation for native flora and fauna. This site could also act as a seed for walkability in the surrounding neighborhoods through the installation of a sidewalk and street trees adjacent to the major road that flanks the site to the south (Figure 8).

The subdivision has 93 single family homes (2.38 homes per acre gross density), only 12 fewer than the original plans for the subdivision called for, set in 13.5 acres of beech/sugar maple forest. This forest contains a carbon pool of 1,268,410.1 kg, and would sequester 252,934.7 kg of carbon per year (Table 8). The canopy is augmented by street tree plantings that include American beech and sugar maples, as well as tree plantings on the lot lines that include eastern white-cedar (*Thuja occidentalis)*, river birch (*Betula nigra)*, and serviceberry (*Amelanchier arborea)* (Table 5). Including prairie planting with C4 grasses and legumes between street trees and on private lands would further enhance carbon sequestration.

Table 7: Carbon sequestered and stored in forest on site under the completed restoration plan

Common Name of Dominant Species	Scientific Name of Dominant Species	Substitution species used	Total carbon sequestered (kg/tree/year)	Total carbon pool size in tree cover (kg/tree)	Total carbon sequestered per year in tree cover per 6.75 acres (kg/year)	Total carbon pool size in tree cover per year per 6.75 acres (kg)
American beech	*Fagus americana*	*Quercus rubra*	40.6	172.3	94,821.3	402,406.7
sugar maple	*Acer saccharum*	_	67.7	370.8	158,113.4	866,003.4
Total Carbon Sequestered per year and stored:					252,934.7	1,268,410.1

In addition to the forest, street and lot line trees, a rainwater woodland behind each home is designed to sequester carbon through maintenance of moist soils and the growth of woody biomass while simultaneously treating and slowing the release of stormwater. These woodlands drain into a swale already present on the site from a previous construction phase. Ultimately rainwater is treated by and slowly released from a rainwater woodland that adjoins the reservoir. In addition to helping keep soils moist, this series of rainwater woodlands will help the subdivision and adjacent ecosystems to adapt to rising water levels and increased storm intensity due to changing climates by providing a buffer against flooding.

Neighborhood residents will have varying opportunities for recreation on public lands. First, a walking path runs through the forest adjacent to the rainwater woodland swale and gives residents a chance to escape into the woods. Its location near the swale prevents further dividing the forest, and allows for a more open feeling than would be found in the surrounding forest. Second, a park planted with eco-lawn, a combination of fescue species, gives the residents of the subdivision a place to gather and play games. A sidewalk cuts through the park and joins the neighborhood's internal sidewalk system to the new street-adjacent sidewalk, increasing walkability to nearby amenities including restaurants and a drug store.

Figure 8: The conservation subdivision design for carbon sequestration

Residential lawn treatments

In addition to the physical design of the neighborhood, certain regulations for the construction, design and management of private lands could assist in enhancing carbon sequestration and creating larger ecological patterns in either the conservation subdivision design, or the ecological restoration design. Key guidelines would include:

1. During construction, minimize soil disruption.
2. During construction, keep large trees and existing ecosystems in place wherever possible
3. All residential yards should be planted with at least 25% native prairie vegetation including C4 grasses and legumes
4. All residential yards should have trees on lot lines.
5. All stormwater must ultimately drain into a rainwater woodland.
6. Grass clippings should be returned to the lawn instead of removed

These guidelines still allow for variation in the way that yards are managed and designed, and could lead to heterogeneity of yard designs based on personal preference (Figure 9). For example, some residents may choose to have the rainwater woodland grow into a part of their backyard design, while some may choose to keep the woodland adjacent to the yard but separate from it. Placement and amount of the prairie plantings in the front, side or backyard could also drastically alter the character of a yard. A sample yard design that follows these guidelines can be found in Figure 10.

Figure 9: Residential lawn alternatives

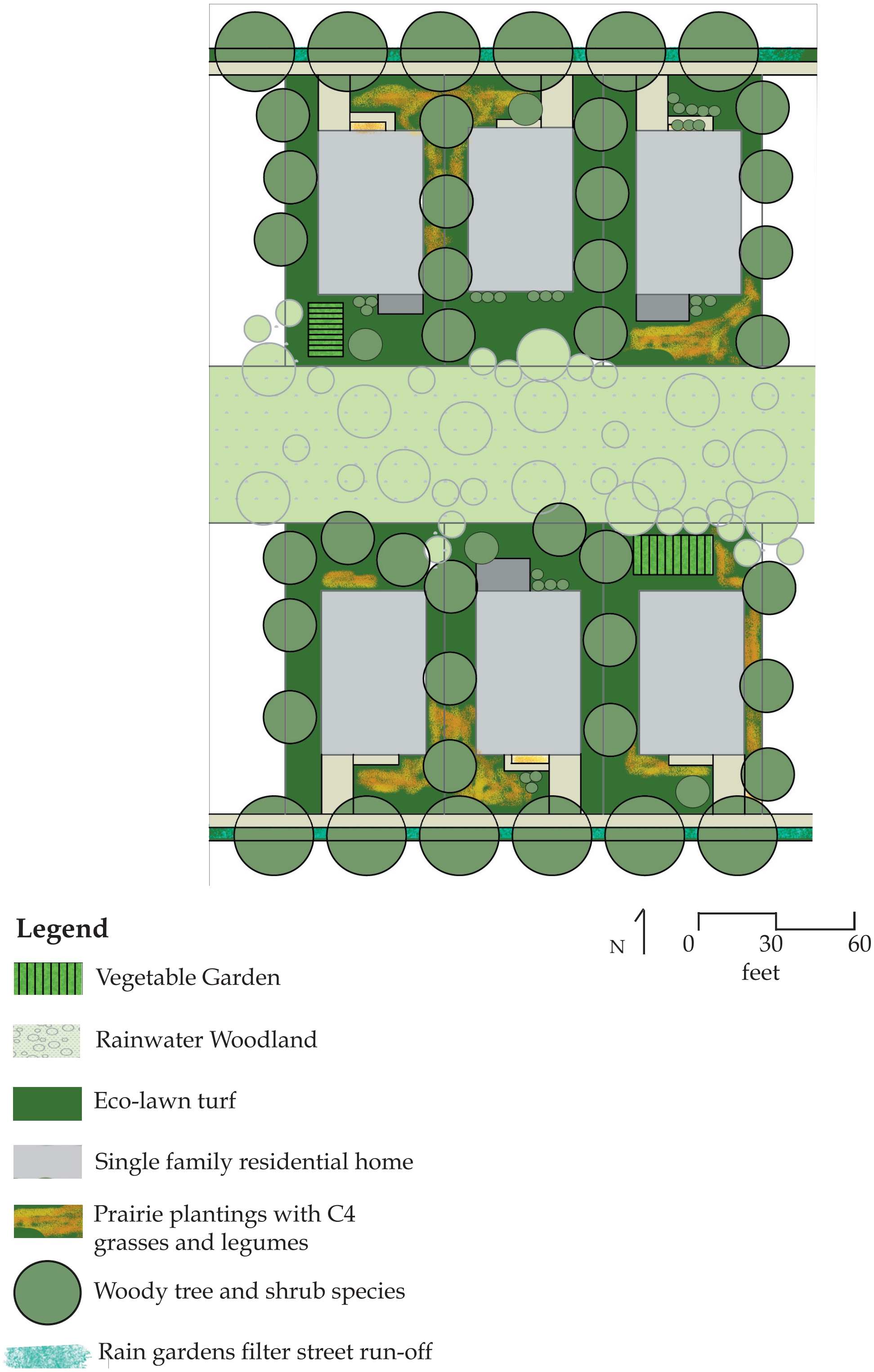
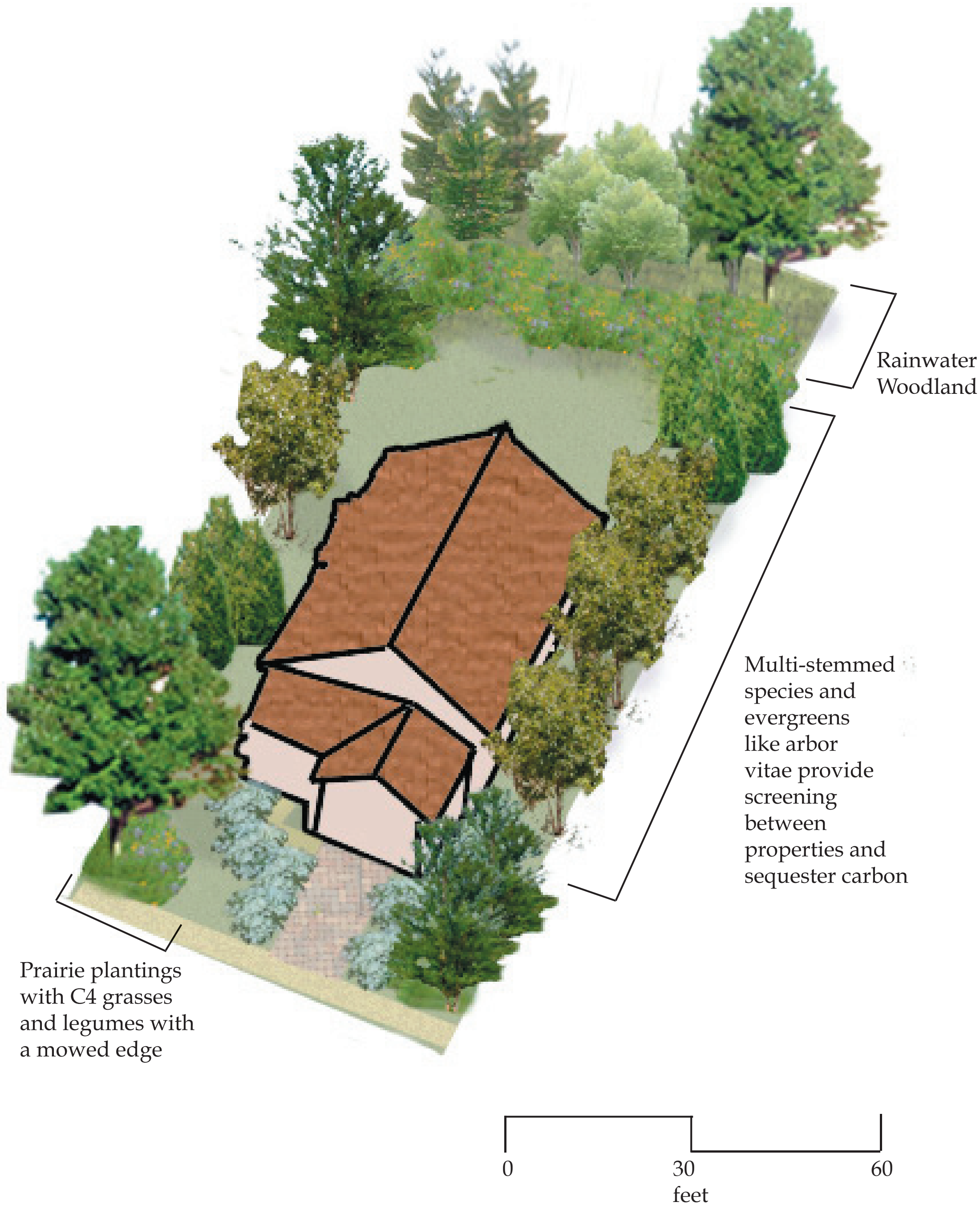


Figure 10: An individual yard design



Chapter VI

Conclusion

Balancing carbon sequestration, ecosystem services and human preferences, as is demonstrated in the conservation subdivision design presented in this thesis, can help to create ecologically and culturally sustainable exurban neighborhoods, and, because of the large area of land occupied by these neighborhoods in the United States, can have a large impact on overall carbon sequestration and ecosystem function.

By making small changes in the way we view subdivision design and planning, we can preserve and enhance a subdivision's ability to adapt to and mitigate against climate change. By maintaining connected, healthy ecosystems, exurban subdivisions can serve as migration linkages for native flora and fauna, and also help to mitigate the impacts of increasing storm intensity and rising water levels. These preserved ecosystems will also continue to sequester carbon in biomass and soils, particularly if they include forests, wetlands or prairies. When construction does occur, minimizing soil disruption will lessen carbon release from exiting in-tact soils; selecting combinations of fast and slowing growing trees and planting herbaceous mixes that include deep rooting herbs, C4 grasses and legumes will help soil carbon stores to recover more quickly on disturbed sites.

The success of conservation subdivisions such as Prairie Crossing show that the design principles that lead to enhanced carbon sequestration, including preserving existing vegetation and soils that are likely storing carbon well, encouraging diverse native plantings, and planning for infiltration and treatment of stormwater, can lead to desirable and culturally sustainable communities. Integrating the methods that increase carbon storage can have little impact on a conservation subdivision's desirability, but can have large a impact on overall carbon sequestration and future climate patterns.

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