Assessment of Carbon Sequestration in the U.S. Residential Landscape

Thesis

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By

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ABSTRACT

Since the industrial revolution, atmospheric concentrations of CO_2 (carbon dioxide) have been increasing. To mitigate or slow the accession of CO_2, research in the areas of terrestrial and soil C (carbon) sequestration is on the rise. This study focuses on the potential of residential landscapes to sequester C.

Urbanized land covers approximately 40.6 Mha (million hectares) in the U.S with approximately 41% of the U.S. urban areas are used for residential neighborhoods. As urbanization increases, the percentage of land converted into residential homes and landscapes is also increasing. Turfgrasses are common in urban areas and cover 16 – 20 Mha in the U.S. which includes residential, commercial, and institutional lawns, parks, golf courses, and athletic fields. Home lawns constitute approximately 6.4 Mha of this turfgrass area. In this study tree, shrub, and lawn C sequestration rates are estimated based on 80 million U.S. single family residential homes with a residential lot size of 2,000 m^2. A typical US home is 93 m^2 with a 2-car garage or carport size of 38 m^2 and a deck or patio of 38 m^2. The house is assumed to be sited in the middle of the lot, with a driveway size of 168 m^2 and a sidewalk size of 122 m^2. The remaining area of 1,541 m^2 is landscape.

The first model estimates the influence of home lawns on net soil organic carbon (SOC) sequestration taking into account the hidden carbon costs (HCC) of fertilizer, mowing, irrigation, and pesticide applications. SOC sequestration and HCC

data rates are established from literature. The net SOC sequestration rate is assessed by subtracting the HCC from gross SOC sequestered. Lawn maintenance practices range from low to high management. Low management or minimal input (MI) includes mowing only, with a net SOC sequestration rate of 63.5 – 69.7 kg C $lawn^{-1}$ yr^{-1}. Do-It-Yourself (DIY) management by homeowners is 107.7 – 124.8 kg C $lawn^{-1}$ yr^{-1}. High management is based on university and industry-standard best management recommendation practices (BMPs) and has a net SOC sequestration rate of 85.3 – 142.9 kg C $lawn^{-1}$ yr^{-1}.

The next model uses the SOC sequestration rates from the previous model and incorporated trees and shrubs using two landscape regimes. The first model has a minimal landscape with one landscape bed in the front of the house 13 m long containing 5 – 10 shrubs approximately 0.6 – 1.2 m in length and width, 2 trees, and a minimal managed lawn. The second model has a maximum landscape with several landscape beds 43 m long surrounding the perimeter of the house containing 17 – 25 shrubs approximately 0.6 – 1.2 meters in length and width, 6 trees, and highly maintained lawn.

Tree sequestration rates are determined by average sequestration rates available from literature and the size of the 10 most common species found in the U.S. shrub sequestration rates are a fraction of that to trees based on relative canopy size. Total or gross C sequestration rate for trees are 3.4 – 5.9 kg C $tree^{-1}$ $yr^{-1}$and 0.07 –

0.24 kg C shrub^{-1} yr^{-1}. A minimal landscaped yard sequesters 111.5 – 139.4 kg C yard^{-1} yr^{-1}. Approximately 7.4% is sequestered by trees, 1.1% by shrubs, and 91.5% by the lawn. A maximum landscape yard sequesters 110.9 – 262.8 kg C yard^{-1} yr^{-1} with 14.9% from trees, 2.6% by shrubs, and 82.5% by the lawn.

Results support the conclusion that residential landscapes are a positive net sink for atmospheric CO_2 under all evaluated levels of landscapes. Even though there are HCC associated with lawn management practices, the potential for soils to sequester C may offset these costs. Residential landscapes have a significant influence on the C cycle. Therefore, these landscapes should be included in regional, national, and global C budget estimations.

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INTRODUCTION

1.1 Atmospheric Carbon and the environment

In the last century, numerous human activities such as land use changes and the burning of fossil fuels have enhanced the greenhouse effect causing global climate change (IPCC, 2007). The greenhouse effect refers to temperature change caused by an increase in atmospheric concentration of trace gases. These changes in climate occur from anthropogenic emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The World Meteorological Organization (2009) indicates that CO_2 is currently at 385.2 parts per million (ppm), N_2O at 321.8 parts per billion (ppb), and CH_4 is at 1797 ppb which are all higher than from pre-industrial times.

The effects of increasing atmospheric carbon (C) concentrations are impacting the environment in multiple ways. One of the major consequences is global temperature increase. The average global temperature is currently increasing at a rate of 0.17°C decade^{-1} (IPCC, 2007). This warming effect can lead to various detrimental environmental transformations such as the disappearance of mountain glaciers, destruction of coral reefs and other ecosystems, and shifts in vegetation zones (IPCC, 2007; Ozenda and Berel, 1990).

Carbon dioxide emissions can be minimized by increasing energy efficiency, increasing usage of renewable energy, and carbon sequestration (capture and secure storage of CO_2 from the atmosphere) (USDOE, 1999).

1.2 Soil organic carbon pool, sequestration, and modeling

The overall global carbon pool consists of five principal carbon pools. These include Ocean (38,400 Gt), Geologic (4,130 Gt), Soil (2,500 Gt), Atmospheric (780 Gt), and Biotic (620 Gt). The Soil pool is greater than both the Atmospheric and Biotic pools combined (Schlesinger, 1977). Estimates range from 1,150-1,220 Pg of C to a depth of 1 meter (m) (Post et al., 1982; Eswaran et al., 1995). Figure 1.1 displays the relationship between the global carbon pools.

Plant C sequestration occurs when plants photosynthesize atmospheric CO_2. During photosynthesis, radiant energy is captured and stored in adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) (Pessarakli, 2008). Energy contained in ATP is used to transfer electrons in NADPH to CO_2. This process forms carbohydrates that are ultimately converted into sugars, glucose, fructose, and sucrose which are used for plant growth. Plant biomass is decomposed forming soil organic C (SOC). Some of the C is released back into the atmosphere by soil and root respiration, as well as by other members of the food chain. An effective strategy for reducing atmospheric CO_2 is to adopt plant management strategies such as land use, nutrient, and water regimens that would maximize C storage in the soil and minimize C loss in the soil (Lal et al., 1998; Kauppi et al., 2001).

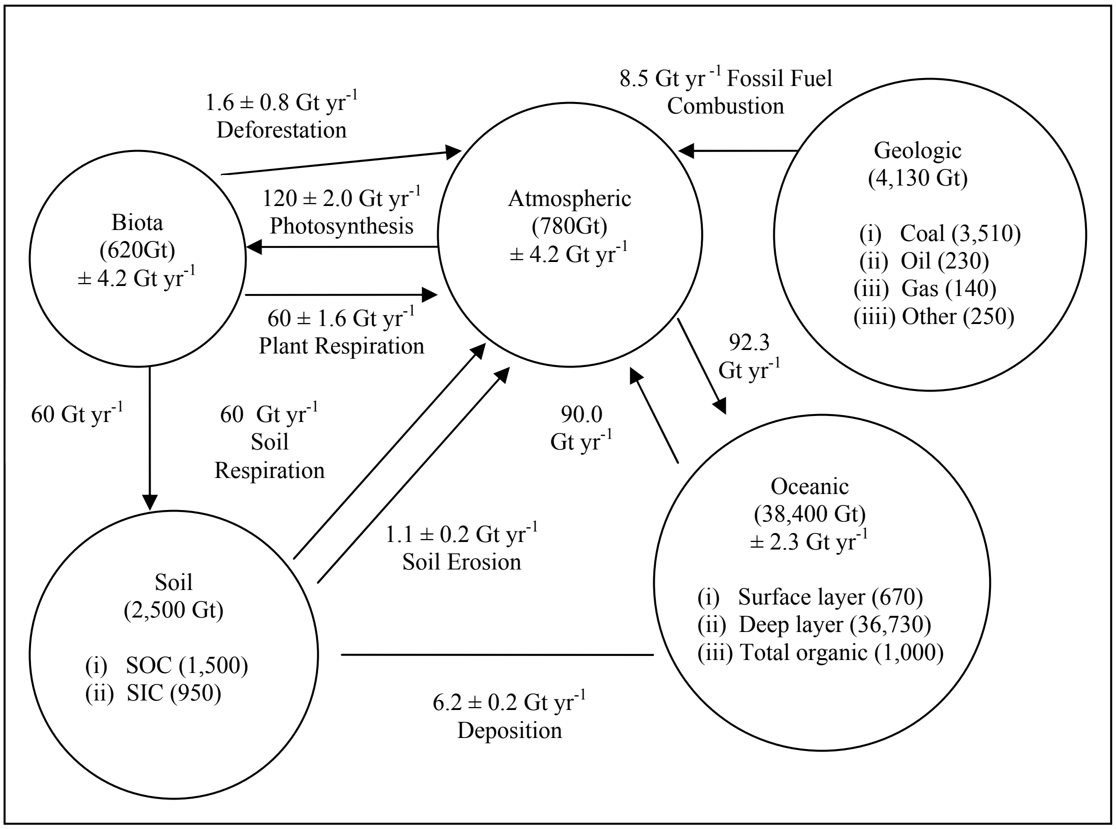

Figure 1.1. The 5 major global carbon pools (Lal, 2008)

There is a large potential for C sequestration in agricultural soils, as well as through land reclamation. Cropland is estimated to have the potential to sequester as much as 0.43 – 0.57 Pg C/yr when adopting agricultural practices such as conservation tillage, converting standard tillage to no till (NT), and adding crop residues, mulch, or cover crops (Lal 1975; 2004a, Blevins et al., 1977; Juno and Lal, 1978; Dick, 1983; Feller et al., 1987; Dalal, 1989; Carter, 1993; Lal and Bruce, 1999; Graham et al., 2002). Reverting land back into its native use, such as abandonment of cultivated land to grassland, can sequester as much as 3.1 g C/m^2/yr to a depth of 10 cm (Burke et al., 1995).

A wide range of techniques exist for estimating SOC potential (Bruce et al., 1999; Smith et al., 1993; Rickman et al., 2001; Smith et al., 2008). Changes in SOC sequestration rates can be measured directly over time (Bruce et al., 1999). Direct measurement is efficient for small scale (plot scale), but can be complicated by spatial and temporal differences in soils over large regional scales (Smith et al. 1993; Bruce et al. 1999). Mathematical modeling of SOC has been well developed, and is widely used to assess SOC sequestration rates under a range of environmental and regional scales (Smith et al., 1993; Bruce et al., 1999; Lal 2004a; Post, 2004; Smith et al., 2008). Modeling has been used extensively to estimate SOC sequestration rate changes resulting from management practices (Bruce et al., 1999; Blanco-Canqui and Lal, 2004; Lal 2004a; 2004b).

1.3 Urban turfgrass soils

Due to urbanization, residential properties are expanding at approximately 700,000 ha per year (Robbins and Birkenholtz, 2003). Urban turfgrass area in the U.S.

is estimated at 163, 800 km^2 (±35, 850 km^2) which includes residential, commercial, and institutional lawns, parks, golf courses, and athletic fields (Milesi et al., 2005). In the United States, the number of single family homes is estimated at 80 million (NGA, 2004) with the average lawn size of 0.08 ha (0.2 acres) (Vinlove, 1995; Augustin, 2007). Urbanization has altered the C cycle, and because of the large amount of land covered by urban areas, these soils need to be evaluated for C dynamics (Pataki, 2006).

The estimated total carbon storage of urban soils in the U.S. is 1.9 x 103 Mt (Pouyat et al., 2006). Converting previous agricultural land into perennial grasses has been shown to sequester 0.33 Mg of C ha^{-1} yr^{-1} (Post and Kwon, 2000) and can increase to 1.1 Mg of C ha^{-1} yr^{-1} with management (Gebhart et al., 1994). Qian and Follett (2002) have modeled SOC sequestration with historic soil testing data in golf courses and have indicated that golf course soils accumulate SOC at a rate of 1.0 Mg per ha/yr, which is comparable to that of grasslands under the Conservation Reserve Program. In grass systems, both soil fertility through fertilization and water application through irrigation have been shown to increase SOC levels (Contant et al., 2001; Quian and Follett, 2002). Home lawns have the potential to sequester C through regular fertilization, however information on SOC dynamics from an urban lawn perspective is lacking. The potential for urban lawns to sequester C is relatively high, but a complete budget of the C cycle related to turfgrass maintenance must be completed to determine actual rates of C sequestration (Pouyat et al., 2006)

1.4 Urban lawn management practices

Urban lawns are managed and cared for through various agronomic and maintenance inputs such as mowing, fertilizer and pesticide applications, and irrigation. There are three types of management practices evaluated in this study: Minimal input (MI), Do-It-Yourself (DIY) average current use, and lawns under Best Management Practices (BMPs).

40 million home lawns receive minimal input and management practices as follows:

1. Homeowners mow once a week from April through October.
2. No Fertilizers, pesticides, or irrigation are applied to the lawn.

Homeowners using DIY management practices are comprised of 30 million single family homes (Augustin, 2007). DIY homeowners do all the management practices themselves and management practices are as follows:

1. Homeowners mow once a week from April through October.
2. Apply fertilizer 1-2 times a year.
3. May apply a herbicide and insecticide.

4. Only 10-15% irrigate the lawn on a regular basis

Lawns under Best Management Practices (BMPs) consist of 10 million home lawns. The BMPs are based on industry standard recommendations (McKinley, 2005) and are as follows:

1. Keep lawn mowed at a height of 2 - 3 inches (one mowing per week April to October)
2. Apply fertilizer 4 times a year with pest problem prevention (weed, insect, or disease) according to the following schedule:
    a. Early Spring: Fertilizer application with weed prevention
    b. Late Spring: Fertilizer application with weed control
    c. Summer: Fertilizer application with insect control
    d. Fall: Fertilizer application (sometimes with weed control)
3. All lawns in this category water the lawn regularly depending on rainfall (2.54 centimeters (cm) of water per week is recommended for turfgrass during the growing season)

The BMPs lawns are comprised of homeowners that care for their lawns themselves (based on the practices above) or hire a lawn service (Augustin, 2007).

1.5 Carbon emissions associated with lawn management practices

Fossil fuel use is directly and indirectly associated with lawn management practices such as mowing, fertilizing, pesticide application, and irrigation. Using Lal's (2004b) conversions for C emissions, all energy use from management practices can be converted into carbon equivalents (CE) (Lal, 2004b). Mowing consumes gasoline (0.84 kg CE kg^{-1} gas), fertilizer and pesticides require production, transportation, storage and transfer (0.1-12.6 kg CE kg^{-1} fertilizer or pesticide), and irrigation requires pumping (16.3 kg CE ha^{-1} yr^{-1}).

The United States Environmental Protection Agency (2004) estimated that the home & garden sector uses around 11,800 Mg herbicides and 2,800 Mg insecticides. DIY homeowners use 907,000 Mg of fertilizer per year (Scotts Co., 2006). Only 10-15% apply supplemental irrigation (NASS, 2003; 2004).

1.6 Tree and shrub carbon sequestration

Urban trees and shrubs have the ability to remove significant amounts of air pollutants, therefore improving environmental quality (Nowak et al., 2006). Urban trees and shrubs are estimated to remove 711, 000 Mt of pollution from the air (Nowak et al., 2006). Carbon storage and gross sequestration from urban trees in U.S. cities range from 19,300 tC in Jersey City to 1.2 million tC in New York City (Nowak and Crane, 2002). The gross carbon urban tree sequestration rate is estimated at 22.8

Mt C yr^{-1} (Nowak and Crane, 2002). Individual tree sequestration is estimated at 1.4 to 54.5 kg C (Nowak and Crane, 2001; England, 2006; Koul and Panwar, 2008).

1.7 Other gas emissions associated with turfgrass/soil systems

Even though CO_2 has the greatest effect on global warming due to the abundant concentration in the atmosphere, N_2O and CH_4 are other GHGs of concern. The global warming potential (GWP) of N_2O and CH_4 can be expressed in terms of CO_2-C equivalents. Through radiative forcing, GWP or the CO_2-C equivalents can be derived. Radiative forcing is the difference in amount of radiation energy entering and exiting the earth's atmosphere. On a 100 year time scale , one unit of N_2O has the same GWP as 310 units of CO_2 and one unit of CH_4 has the same GWP as 21 units of CO_2 (IPCC, 2001).

Emissions of N_2O occur from both natural and anthropogenic sources. Sources include soils, oceans, fossil fuel combustion, fertilizer use, biomass burning, and other industrial processes (WMO, 2009). One third of N_2O emissions are anthropogenic sources (WMO, 2009). The pre-industrial atmospheric background of N_2O concentration was 270 ppb and has been rising approximately 0.76 ppb yr^{-1} (Bockman and Olfs, 1998; WMO, 2009).

Being a main component of natural gas, CH_4 is derived from both natural and anthropogenic sources such as wetlands, termites, ruminant animals, fossil fuels, biomass burning, and land-fills (WMO, 2009). Pre-industrial levels of CH_4 were approximately 700 ppm with an average growth rate of 2.4 ppb year^{-1} (CAST, 2004; WMO, 2009).

The effect of rapid urbanization on the GHG budget is an area of increasing interest. Urban greenspaces, and more specifically turfgrasses, need to be evaluated to address the role of turfgrass systems on GHG fluxes. Limited information is available on the field comparisons of soil-atmosphere exchange of N_2O and CH_4 in the urban ecosystem. This section contains a review of current literature on N_2O and CH_4 fluxes from turfgrass/soil ecosystems.

1.7.1 Nitrous oxide emissions

Determining N losses from the turfgrass and soil ecosystem is beneficial for developing an appropriate fertilization program that promotes healthy turfgrass, as well as addressing the environmental concerns associated with N losses. Losses of N from turfgrass sites include denitrification, leaching, volatilization, runoff, and infrequently, erosion (Tisdale et al., 1985; Petrovic, 1990; Foth and Ellis, 1997; Baird et al., 2000).

Denitrification losses are most likely very low for many turgrass/soil conditions (Carrow et al., 2001). Some conditions, such as soils with compaction, algae covered surfaces, or poor drainage may be environments which accentuate denitrification. The N_2O loss from soils is well documented, but limited studies are available on denitrificaiton and the loss of N from turfgrass/soil ecosystems.

The greenhouse gas balance was evaluated in grasslands in Europe looking at CO_2, N_2O, and CH_4 (Soussana et al., 2007). Sites included unfertilized and fertilized plots. Nitrogen fertilizer applications ranged from 175 – 300 kg N ha^{-1} yr^{-1}. N_2O emissions were measured at all sites with both static chambers and tunable diode laser equipment and converted to CO_2-C equivalents using GWP at the 100 year time scale of 310 (Flechard et al., 2007). The average N_2O flux reached 13 g CO_2-C equivalents m^{-2} yr^{-1} and ranged anywhere from negative fluxes to 87.2g CO_2-C equivalents m^{-2} yr^{-1} (Soussana et al., 2007). N_2O fluxes ranged from 0.1 – 87.2 CO_2-C m^{-2} yr^{-1}equivalents for fertilized plots, and (-) 2.9 to 29.2 CO_2-C m^{-2} yr^{-1} for unfertilized treatments.

Denitrification losses from fertilized Kentucky bluegrass (*Poa pratensis*) sod on silt and silt loam soils were 0.1 – 0.4% of applied N when soils were less than 80% saturated and fertilized with 4.5 g N m^{-2} (Mancino et al., 1998). No detectable N_2O-N losses occurred from unfertilized soils < 80% saturation of moisture content. When soil saturation reached > 80%, denitrification losses increased to approximately 0.1 – 6.6 % of applied N. Smith and Tiedje (1979) also reported an increase in denitrification at soil water levels > 75% of saturation point. Peak emissions occurred between 48 – 60 mg N m^{-2} d^{-1}. Others have reported emissions ranging from 50 – 90 mg N m^{-2} d^{-1} on ryegrass swards (*Lolium multiflorum)* (Demead et al., 1979; Smith et al., 1982; Anonymous, 1983; Sextone et al., 1985). Longer periods of N_2O-N efflux occur at soil saturation levels of ≥ 80% (Mancino et al., 1998).

Mancino (1988) also compared the effect of temperature on denitrification using constant soil moisture at 75% of saturation. Efflux increased linearly with an increase in temperature from 22 – 30 ºC. Total losses of N were less than 0.1% of the N-fertilizer applied (Mancino et al., 1988). When soils increased in temperature and soil saturation, large denitrification losses occurred, representing 44.6 – 92.6% of the N applied (Mancino et al., 1988). Denitrification rates reached a maximum at 30 ºC. A similar trend was documented by Bremner and Shaw (1958).

Maggiotto (2000) compared N_2O emissions from loam-textured soils under different types of N fertilization on ryegrass plots with no pesticide or irrigation applications applied. Fertilizer types evaluated were urea, slow-release urea, and ammonium nitrate at 50 kg N ha^{-1}. The study was initiated for three seasons during 1995 – 1997. Over three seasons, the fertilized plots had higher emission rates of N_2O-N than the unfertilized or control plots. The emission rates from control plots ranged from (-)0.4 to 0.1 g N_2O-N ha^{-1} d^{-1}, while that from the fertilized plots ranged from 0.7 – 22.0 g N_2O-N ha^{-1} d^{-1}. In 1995 and 1996, the highest N_2O emissions were from ammonium nitrate during 1995 and 1996 and from slow-release urea in 1997. The maximum loss of N as % if applied fertilizer in the form of N_2O in 1996 was 1.66% from ammonium nitrate. The highest emission rate in 1997 was 0.52% for the slow-release urea and 0.33% for ammonium nitrate. The magnitude of loss of N_2O from ammonium nitrate was within the same range as that reported by Eichner (1990) of about 0.04 – 1.71%. Losses from urea ranged from 0.05 – 0.33% of applied N. The N_2O emissions averaged 1.25% of N applied with ammonium nitrate yielding the highest N_2O fluxes (Maggiotto, 2000).

Kaye (2004) studied the fluxes from CH_4 and N_2O of urban soils to the atmosphere, and compared urban and non-urban ecosystems. The ecosystems studied consisted of urban lawn, native shortgrass steppe, dryland wheat fallow, and flood-irrigated corn. Urban lawn areas were regularly irrigated and fertilized twice a year (once in spring and once in the fall) at the rate of 11 g N m^{-2} (110 kg N ha^{-1}). Irrigated corn was fertilized once in the spring at a rate of 15 g N m^{-2} (150 kg N ha^{-1}). No other treatments were irrigated or fertilized. The average N_2O flux from urban soils to the atmosphere was 0.24 g N m^{-2} y^{-1} (2.4 kg N ha^{-1} yr^{-1}). This flux is comparable to that from irrigated corn (*Zea mays*), but is more than that from wheat (*Triticum aestivum*) fallow or native grasslands. The percent of N_2O fluxes from N applied was 2.2% for urban lawns and 1.4% for irrigated corn (Kaye et al., 2004).

Bowman and associates (1987) evaluated N_2O fluxes in turfgrass using a range of fertilizer rates and types. The experiment was conducted with perennial ryegrass on a Chase silt loam soil from 2003 – 2004. Three fertilizer types included a high rate of urea (250 kg ha^{-1} yr^{-1}), a low rate of urea (50 kg ha^{-1} yr^{-1}), and a high rate of ammonium sulfate (250 kg ha^{-1} yr^{-1}). Plots were irrigated with 15 mm of water after fertilization to reduce ammonia volatilization (Bowman et al., 1987). Throughout the summer, plots were irrigated three times a week or as needed to prevent drought stress.

Higher rates of N_2O flux occurred on plots receiving a high rate of urea and a high rate of ammonium sulfate than from those receiving low rates (Bowman et al., 1987). N_2O fluxes of 1.65 kg N ha^{-1} yr^{-1} were observed from plots that received the high rate of urea compared to 1.01 kg N ha^{-1} yr^{-1} from those which received the low rate. The high rate ammonium sulfate produced 1.60 kg ha^{-1} yr^{-1}. A significant difference of 63% in N_2O fluxes was observed between the high and low rate of urea, but no difference in flux was observed among fertilizer types. The high rate of urea and high rate of ammonium sulfate emitted approximately 0.65% and 2.02% of N applied, respectively (Bowman et al., 1987). These results are similar to those reported by Kaye (2004). The magnitude of N_2O fluxes ranged from (-)22 µg N_2O-N m^{-2} h^{-1} during the winter to 407 µg N2O-N m^{-2} h^{-1} after fertilizing in the fall. N_2O fluxes were higher for the period of 2-3 weeks after fertilizer application, and then dropped to natural background levels (Bowman et al., 1987).

Pataki (2006) evaluated N_2O fluxes in relation to temperature differences in tall fescue (*Festuca arundinacea*) under two levels of fertilizer application. Three plots were heated by infrared lamps and three plots served as a control. The heated plots resulted in an increase in mean daily temperature of 3.5ºC at the soil surface. The common homeowner turfgrass fertilizer formula of 29-3-4 was applied at different times throughout the year to simulate low and high-intensity management regimes. The low-intensity management regime included two applications (one in spring and one in summer) for a total of 76.4 kg of fertilizer ha^{-1} yr^{-1}. The high-intensity management regime included four applications (two in the spring and two in the summer) for a total of 118.5 kg ha^{-1} yr^{-1}. Turfgrass was irrigated only when needed to prevent drought stress.

The N_2O fluxes were within the same range as reported in previous turfgrass studies. The N_2O fluxes were variable for all treatments, and increased immediately following fertilization events, but declined shortly thereafter. The highest fluxes of 2.0 mg N m^{-2} d^{-1} were monitored following the fertilization in the spring for the plots with high temperature and low intensity fertilizer applications (Pataki, 2006). Even though lawns were watered frequently during late summer, soil moisture was low due to high air temperatures. The fluxes were higher from the high temperature and low-intensively managed plots compared to the control and controlled temperature plus high-intensively managed plots, but no statistical differences were observed among treatments (Pataki, 2006).

The N_2O emissions under experimental plots from all of the literature reviewed ranged from 0.3 – 60.0 mg N m^{-2} d^{-1}. Measurements of N_2O emissions include those from various turfgrass ecosystems under a range of fertilizer applications. Percent of N fertilizer lost ranged from 0.01 – 92.6% of N applied. The variability in the emissions and percent fertilizer lost were most likely due to the differences in regional turfgrass/soil ecosystems and management regimes. Turfgrass systems can emit N_2O in similar amounts as those emitted from grassland or cropland ecosystems. However, denitrification losses are low for most turfgrass systems (Carrow et al., 2001). In general, N_2O emissions are low from application of ammonium based fertilizers when denitrification is the dominant process (high water filled pore space), and from nitrate-based fertilizers when nitrification (low water filled pore space) is the dominant mechanism (Maggiotto, 2000).

Larger denitrification losses occur following fertilization of turf, but do not persist for a long periods of time, and emissions return to the background levels shortly after application (Mancino, 1988). Thus, emissions of N_2O by denitrification losses may not be a serious problem in the turfgrass system unless soils reach a high temperature and are water saturated which enhance denitrificaiton. The data on rates of N_2O emissions under natural background conditions are limited. Therefore, comparisons of N_2O fluxes from fertilized grass to natural background levels are rarely documented.

1.7.2 Methane emissions

Soil can be a source or sink for CH_4 depending on soil properties and processes (Brady and Weil, 2008). Methanogenesis occurs when the soil is saturated for a long period of time, such as in with rice paddies and wetlands (CAST, 2004). When soils are anaerobic, they produce CH_4 as soil microbes decompose soil organic matter (Brady and Weil, 2008).

Approximately one billion Mg (10^9 Mg = 1 Gt) of methane is absorbed and reduced from the atmosphere by methanotrophic bacteria (Brady and Weil, 2008). The bacteria produce the enzyme *methane monooxygenase*, using CH_4 as an energy source through oxidation (CAST, 2004; Brady and Weil, 2008). Other uptake estimations range from 20 – 60 Tg yr^{-1} globally (Reeburgh et al., 1993). Regional ranges include 23 μg m^{-2} h^{-1} for taiga soils (Whalen et al., 1991), 28 μg m^{-2} h^{-1} for desert soils (Striegl et al., 1992), 20 – 50 μg m^{-2} h^{-1} in temperate grassland (Mosier et al., 1997), and 38 – 60 μg m^{-2} h^{-1} in temperate forests (Steudler et al., 1989; Robertson et al., 2000).

Land use changes and management practices affect the biological processes associated with CH_4 uptake (Prueger et al., 1995; CAST, 2004; Brady and Weil, 2008). Land use changes from native grasslands to managed crops and pastures can reduce the amount of CH_4 uptake (Keller et al., 1990; Mosier et al., 1991, 1997;

Nesbit and Breitenbeck, 1992; Robertson et al., 2000). Fertilized grasslands and cropland systems show a decrease in the capacity of soil to oxidize methane compared with natural ecosystems (Bronson and Mosier, 1993; Mosier et al., 1997; Robertson et al., 2000). However, nitrogen supplied in organic form can enhance methane oxidation as reported from long term experiments conducted in Germany and England (Willison et al., 1996).

Turfgrasses can be a sink or source for CH_4. Oxidation of CH_4 into grass systems is lower in mineral fertilized grass than in unfertilized grass systems. Yet, even fertilized grass systems are a sink for atmospheric CH_4. This trend is most likely due to the availability of ammonium stimulating; ammonium-oxidizing bacteria which limits the activity from the methane oxidizing bacteria (Brady and Weil, 2008).

1.8 Research goals and objectives

The goal of this research is to assess the C sequestration potential of residential landscape in the United States with the following objectives:

1. Model SOC sequestration in home lawns with Minimal Input, Do-It-Yourself management, and Best Management Practices
2. Model tree, shrub, and lawn carbon sequestration for the typical residential U.S. yard.

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CHAPTER 2

MODELING CARBON SEQUESTRATION IN HOME LAWNS

2.1 Abstract

Soil organic carbon (SOC) sequestration and the impact of carbon (C) cycling in urban soils are themes of increasing interest. There are 80 million U.S. single family detached homes comprising of 6.4 million ha of lawns with an average size lawn of 0.08 ha. The potential of SOC sequestration for U.S. home lawns is determined from the SOC rates of turfgrass and grasslands. Net SOC sequestration in lawn soils is estimated using a simple mass balance model derived from typical homeowner lawn maintenance practices. The average SOC accumulation rate for U.S. lawns is 80.0 kg C $lawn^{-1}$ yr^{-1}. Additional C accumulation results from fertilizer and irrigation management. Hidden C costs (HCC) of typical lawn management practices include mowing, irrigating, fertilizing, and pesticide application. The net SOC sequestration is assessed by subtracting the HCC from gross SOC sequestered. Lawn maintenance practices range from low to high management. Low management or minimal input (MI) includes mowing only, with a net SOC sequestration rate of 63.5 – 69.7 kg C $lawn^{-1}$ yr^{-1}. Do-It-Yourself (DIY) management by homeowners is 107.7 – 124.8 kg C $lawn^{-1}$ yr^{-1}. High management is based on university and industry-standard best management practices (BMPs) and has a net SOC sequestration rate of 85.3 –

142.9 kg C lawn^{-1} yr^{-1}. Results support the conclusion that lawns are a positive net sink for atmospheric carbon dioxide (CO_2) under all evaluated levels of management practices with a national technical potential ranging from 63.5 – 142.9 kg C lawn^{-1} yr^{1}.

Keywords Soil C sequestration, global warming, lawn management, turfgrass, hidden C costs

2.2 Introduction

Research in abrupt climate change and the C cycle have become major thematic foci since the 1990's. Soil C sequestration is one of the strategies proposed to help stabilize atmospheric carbon dioxide (CO_2) (Lal, 2004a; Smith, 2007). The interest in urban soils is derived from the fact that 75% of the US population lives in urban areas where individuals can potentially affect carbon sequestration in their home landscape (USCB, 2010). Lawn grasses are the predominate plants in the urban landscape in which homeowners manage the growth (Beard, 1973; Thurn et al., 2004). A simple C footprint benchmark of home lawns can be developed from three components; the capacity of urban soils to store C, the capability of grass plants to fix and sequester C, and the C footprint of lawn maintenance practices.

Several studies have evaluated C sequestration potential of agricultural and urban soils as one of several options to stabilize atmospheric CO_2 abundance (Smith et al., 1993; Bruce et al., 1999; Blanco-Canqui and Lal, 2004; Pouyat et al., 2002; Lal et al., 2004a; Leifield, 2006; Pataki et al., 2006; Pouyat et al., 2006; Lal, 2008; Pickett et al., 2008; Smith et al., 2008). Soil organic carbon comprises of the historic accumulation of humus in the soil. Long term storage of SOC occurs when humus reaches a point of stability and gains exceed losses (Whitehead and Tinsley, 2006). Variations in the SOC pool occur within ecosystems because of differences in rate of soil organic matter (SOM) decay via microbial decomposition, temperature fluctuations, and precipitation amounts and frequencies (Pouyat et al., 2002).

The SOC pool is important for soil structure maintenance and other ecosystem services (Lal, 2004a; 2009). It improves numerous soil properties and processes including soil tilth, aggregation, plant available water and nutrient capacities, reduction in susceptibility to erosion, and filtering of pollutants (Blanco-Canqui and Lal, 2004). The SOC pool is depleted through soil cultivation and land use conversion (Post and Kwon, 2000; Lal, 2004a), and can be enhanced through those soil conservation and restoration practices which add biomass-C and rate of its decomposition (Lal, 2004a). Common practices include no till (NT) agriculture, perennial plant cover, fertilization, irrigation, and organic amendments (Post and Kwon, 2000; Lal, 2004a; Post et al., 2004). Grasses are a perennial plant cover and have the potential to store SOC long term in the soil (Pataki et al., 2006; Pouyat and Nowak, 2006).

Urban lawns are potential C sinks (Pouyat, 2002; 2006; Pataki, 2006). Urbanized land covers approximately 40.6 million hectares (Mha) in the U.S. (UN, 2004a). National Census Bureau estimates that 75-80% of North American population lives in urban areas (UN, 2004b). The urban land use is 3.5% to 4.9% of the U.S. land area (NAR, 2001; Nowak et al., 2001). As urbanization increases, the percentage of land converted into turfgrass is also increasing (Qian and Follett, 2002; Bandaranayake et al., 2003; Milesi et al., 2005; Lorenz and Lal, 2009a).

Approximately 41% of U.S. urban area is used for residential neighborhoods (Nowak et al., 1996; 2001). Turfgrasses cover 16 - 20 Mha in the U.S which includes residential, commercial, and institutional lawns, parks, golf courses, and athletic fields (Anonymous, 1996; Milesi, 2005). There are 80 million U.S. single family detached homes with 6.4 Mha of lawns (NGA, 2004; Augustin, 2007). Home lawns size varies regionally (north to south and east to west), as well as at a locally (rural versus suburban). Home lot size differs from that of home lawn size (NAR, 2001). Home lot size includes the house and land owned by the homeowner, where home lawn size includes the area covered by turfgrass. In this study, the average size of household lawns in the U.S. is 0.08 ha (Vinlove, 1995; NAR, 2001; Augustin, 2007).

Estimated C pool in U.S. urban soils is 7.70 ± 0.20 kg m^{-2} (Pouyat et al., 2006). Converting previous agricultural land into perennial grasses sequesters 0.3 Mg C $ha^{-1}yr^{-1}$ (Post and Kwon, 2000), and can increase to 1.1 Mg C $ha^{-1}yr^{-1}$ with fertilizer and irrigation management (Gebhart et al., 1994; Contant et al., 2001; Quian and Follett, 2002). Qian and Follett (2002) modeled SOC sequestration with historic soil testing data from golf courses and reported that golf course soils sequester SOC at a rate of 1.0 Mg $ha^{-1}yr^{-1}$. Grasslands under the conservation reserve program also accumulate SOC at a similar rate (Qian and Follett, 2002). Ohio farmland converted to golf courses sequesters C at an initial rate of 2.5 – 3.6 Mg C $ha^{-1}yr^{-1}$ due to permanent ground cover and increased management inputs of fertilizer and irrigation (Selhorst, 2007). All of these C sequestration rate studies include sampling of less than or equal to 30 cm of the top soil.

While home lawns have potential to sequester C, information on SOC dynamics for urban lawns is limited (Pouyat et al., 2006). The potential for urban lawns to sequester C is high due to perennial turfgrass cover. Soils beneath established lawns are undisturbed, and are therefore comparable to perennial grasslands and NT agricultural systems (Falk, 1976; 1980; Qian and Follett, 2002; Follett et al., 2009). Lawns have capability to produce similar biomass as corn (*Zea mays*), wheat (*Triticum aestuvum*), and prairie grasses (Falk, 1976; 1980; Qian and Follett, 2002). A complete turfgrass C cycle accounting for turfgrass maintenance practices of mowing, irrigation, fertilizing, and applying pesticides must be completed to determine net C sequestration rates (Bandaranayake, 2003; Pouyat et al., 2006; Pickett et al., 2008).

In general, fertilizer and irrigation practices increase SOC sequestration rates (Glendining and Powlson, 1991; Campbell and Zentner, 1993; Gregorich et al., 1996; Paustian et al., 1997; Lal, 2003). Thus, use of fertilizers and irrigation as lawn maintenance practices would increase plant biomass, and enhance the SOC pool. An increase in input of plant biomass increases the rate of humification (Duiker and Lal, 2000; Puget and Lal, 2005).

A wide range of techniques exist for estimating the technical potential of SOC sequestration (Smith et al., 1993; Bruce et al., 1999; Rickman et al., 2001; Smith et al., 2008). Changes can be measured directly over time (Bruce et al., 1999). Direct measurements are efficient for small scale (plot scale), but can be complicated by spatial and temporal differences in soils over large regional scales (Smith et al., 1993; Bruce et al., 1999). Mathematical modeling of SOC has been well developed, and is widely used to investigate SOC under a range of environmental and regional scales (Smith et al., 1993; Bruce et al., 1999; Lal, 2004a; Post, 2004; Smith et al., 2008). Modeling has been used extensively to estimate SOC changes resulting from management practices (Bruce et al., 1999; Blanco-Canqui and Lal, 2004; Lal, 2004a; 2004b).

Therefore, the objective of this research is to describe a simple mass balance model that predicts the rate of SOC sequestration under a range of management scenarios for single family home lawns in diverse eco-regions of the U.S. The model specifically explains methods to estimate the net SOC sequestration rate for homes under minimal input (MI), the Do-It-Yourself (DIY) homes based on average current practices, and homes using university best management practices (BMPs).

2.3 Material and methods

The SOC sequestration rate for U.S. home lawns is modeled using data available from literature. The net SOC sequestration rate is the amount of gross C sequestered minus hidden C costs (HCC) of lawn maintenance practices expressed as C equivalents. Home lawns are cared for in a wide intensity of agronomic and maintenance inputs including mowing, applying fertilizer and pesticides, and irrigating. Forty million home lawns have minimal lawn care inputs (mowing only), 30 million lawns are maintained by the homeowner, and 10 million use a lawn care service or apply fertilizer multiple times a year (Augustin, 2007).

Homeowner's management and preferred practices were based on three categories of management regimes (Augustin, 2007). The DIY lawn practices focus on average current lawn maintenance practices to calculate average net SOC sequestration rate in U.S. home lawns. Estimates of lawn maintenance practices for MI and BMPs are calculated to benchmark net C sequestration rate of low to high lawn maintenance regimes. The parameters, data, and assumptions used in the model are summarized in Table 2.1. Net C sequestration is comprised of gross SOC sequestered minus the HCC of lawn maintenance practices (Eq. 2.1).

Net C sequestration Rate = Gross SOC sequestration Rate – HCC………**Equation 2.1**

2.3.1 Soil organic carbon sequestration

Net SOC sequestration rate estimates are compiled using data in the literature for NPP and previous SOC sequestration rate studies (Table 2.2 and 2.3). The NPP is used to estimate the average rate of SOC accumulation in the soil after plant material has decayed (Smith et al., 1993). The only data sets selected for use in this study consist of gross primary productivity minus respiration using both belowground (root) and aboveground (shoot) growth for U.S. grasslands and turfgrasses (Table 2.2). Grassland sites vary in geography and climate across the U.S. The NPP data used in this model includes direct measurements of dry plant biomass over 12 different sites. The average range of productivity is 6.2 - 13.1 Mg dry matter ha^{-1} yr^{-1} which was derived by averaging all of the low rates and high rates to get one average range of productivity. Each year, approximately 10% of biomass added to the soil may be humified (Duiker and Lal, 2000; Puget and Lal, 2005). This is the amount of plant material left as SOC after detritus and microbial turnover (Schiemel et al., 2004). Thus, SOC sequestration in soils by NPP is estimated at 0.6 - 1.3 Mg C ha^{-1} yr^{-1} after adjusting for the humification efficiency

Category	# of Lawns (millions)	Mowing yr^{-1}	# of Irrigated Lawns (millions)	Fertilizer	Pesticide Use
MI	40	28	None	None	None
DIY	30	28	3- 4.5 (10-15%)	9.07×10^5 Mg Fertilizer sold yr^{-1} - 2.63×10^5 Nitrogen - 2.70×10^4 Phosphorus - 3.60×10^4 Potassium	EPA reported pesticide use estimations in Mg yr^{-1} - 5.9×10^3 Mg herbicide - 1.4×10^3 Mg insecticide
BMPs	10	28	10	Industry-standard recommendations in kg ha^{-1} yr^{-1} - 147 – 250 Nitrogen - 30 – 50 Phosphorus - 60 – 100 Potassium	Industry-standard recommendations in kg ha^{-1} yr^{-1} - 1 pre-emergent herbicide at 1.77 - 1 post emergence herbicide combo at 2.54 - 1 insect control at 0.09

Table 2.1. Summary of parameters, data, and assumptions used in the model development

Biomass/Region	Dry plant Weight ($Mg\ ha^{-1}\ year^{-1}$)	Reference
Desert grasslands	2.00 – 3.00	Woodwell and Whittaker (1968)
Desert grasslands	2.25 – 3.79	Sims and Singh (1978)
Mountain grassland	8.00 – 9.20	Sims and Singh (1978)
Shortgrass prairies	5.70 – 13.00	Sims and Singh (1978)
Mixed prairies	5.20 – 14.25	Sims and Singh (1978)
Tallgrass prairie	7.00 – 13.53	Sims and Singh (1978)
Tallgrass prairie	9.92 – 11.32	Kucera et al. (1967)
Tropical grasslands	2.00 – 20.00	Leith (1975)
Tropical grasslands	15.00 – 30.00	Woodwell and Whittaker (1968)
Temperate grassland	6.76	Van Hook (1971)
Temperate grasslands	1.00 – 15.00	Leith (1975)
Temperate Lawns	10.00 – 17.00	Falk (1976; 1980)
Average Biomass	**6.24 – 13.07**	

Table 2.2. Annual net primary productivity of dry plant weight (roots and shoots) of grasslands and turfgrass in the U.S.

Land Use/Management	Average SOC Accumulation (Mg C ha^{-1} yr^{-1})	References
Cultivated reseeded to grass	0.80	Bruce et al. (1999)
Low – High Grassland Management	0.54	Contant (2001)
Cultivated to wheatgrass	0.189	White et al. (1976)
Cultivated to Russian wildrye	0.069	White et al. (1976)
Cultivated to abandoned grassland	0.031	Burke et al. (1995)
15 Golf courses -fairways and greens	1.00	Qian & Follett (2002)
10 golf courses - rough	2.50	Selhorst (2007)
10 golf courses - fairway	3.60	Selhorst (2007)
Turf- greens	0.90	Bandarnayake et al. (2003)
Turf -fairways	1.00	Bandarnayake et al. (2003)
Cultivated to perennial grasslands	1.10	Gebhart et al (1994)
Average SOC Accumulation	**1.07**	

Table 2.3. Annual soil organic carbon accumulation rates of grasslands and turfgrass in the U.S.

The SOC sequestration data includes U.S. grasslands and areas converted to grasslands or turfgrass (Table 2.3). Sites vary in geography and climate across the U.S. The SOC sequestration data consists of direct soil measurements or a combination of direct soil measurements and modeling techniques. The SOC sequestration rates from grassland and prairie sites are similar to the SOC from managed turfgrass (Pouyat et al., 2002; Qian and Follet, 2002). The average rate of SOC sequestration is 1.07 Mg C ha^{-1} yr^{-1} (Table 2.3)

The SOC sequestration models are often developed using the net primary productivity (NPP) data (Smith, 2008). The present model uses NPP and SOC sequestration studies for grasslands specifically selected to compare two different approaches. Both NPP and SOC sequestration rates fall within the same range of 0.6 to 1.3 Mg C ha^{-1} yr^{-1}. Comparisons of these models support the conclusion that SOC sequestration ranges are representative of the U.S. average rates. The average rate of SOC accumulation is 1.0 Mg C ha^{-1} yr^{-1} for the U.S. This average was derived from a total average of low NPP (0.64 Mg C ha^{-1} yr^{-1}), high NPP (1.30 Mg C ha^{-1} yr^{-1}), and SOC sequestration averages (1.07 Mg C ha^{-1} yr^{-1}). This equates to 80.0 kg C $lawn^{-1}$ yr^{-1}.

2.3.2 Influence of fertilizer and irrigation on SOC accumulation

Fertilizer and irrigation practices can increase SOC pool by increasing the amount of biomass production (Lal et al., 1999). The proposed model uses experimental data relating the rate of biomass production to N application. Grass receiving fertilizer produces 7% – 298% more dry biomass than unfertilized grass (Graber and Ream, 1931; Harrison, 1934; Lovvorn, 1945; Juska et al., 1955; Beaty et al., 1960; Madison, 1961; Sullivan, 1961; Juska and Hanson, 1968; Warnes and Newell, 1968). The rate of increase in the SOC pool by irrigation is 50.00 - 100.0 kg C ha^{-1} yr^{-1} (Lal et al., 1999). In the present study, the rate of increase in the SOC pool is estimated at 4.0 – 8.0 kg C $lawn^{-1}$ yr^{-1}(Equation 2.2). Each set of SOC sequestration data is summed to attain the net SOC sequestration (Eq. 2.3).

Low **High** ……………..**Equation 2.2**

$$\frac{50kg\ C}{ha} \times \frac{0.08ha}{lawn} = \frac{4.0kg\ C}{lawn} \qquad \frac{100kg\ C}{ha} \times \frac{0.08ha}{lawn} = \frac{8.0kg\ C}{lawn}$$

Net SOC Sequestration Rate = SOC Sequestration +
Fertilizer SOC Sequestration + Irrigation SOC Sequestration…….……...**Equation 2.3**

2.3.3 Hidden carbon costs

Lawn management practices of mowing, irrigating, fertilizing, and applying pesticides are derived from energy-based inputs. The HCC are the amount of energy expended by various lawn maintenance practices from manufacturing to the amount used in lawn care. Energy was calculated in units of C equivalents (CE) and expressed on a C weight bases (Lal, 2004b). Turfgrass management practices are converted to kg CE, which are summed for each maintenance practice to estimate the HCC (Eq. 2.4).

HCC= CE Mowing + CE Irrigation + CE Fertilizer + CE Pesticides……**Equation 2. 4**

The HCC are used in the model to compute net SOC sequestration rates. The HCC of mowing is based on typical homeowner practices of mowing once per week from April to October, for a total of 28 mowings yr $^{-1}$. Majority of homeowner lawn mowers are walk-behind with a 2.2 – 3.7 kilowatt (kW) gasoline powered motor. Mowers in this category consume 12.7 to 20.4 ml gasoline min^{-1} (Priest, 2000). The CE of gasoline is 0.8 kg CE kg $^{-1}$ gasoline (Lal, 2004b). Mowing time for average size lawn is estimated at an average walking speed of 4.0 km hr^{-1} mowing a 0.5 m x 1509.5 m (0.08 ha) strip and doubling time for making mower turns (Tudor-Locke, 2003; Weil, 2009). Mowing consumes 10.3 – 16.5 kg CE lawn^{-1} yr^{-1}. This rate is established for all management levels (Eq. 2.5).

$$\frac{4.02km}{60\min}\times\frac{1m}{0.001km}=\frac{4020m}{60\min}\times\frac{1509.46}{X\ \min}=23\min(2)=46\min$$

$$46\min\times 28\ mowings=1288\ \min/yr$$

Low ……………………Equation 2.5

$$\frac{12.7ml\ gas}{\min}\times\frac{1288\min}{year}\times\frac{1lt}{1000ml}\times\frac{739g}{1lt\ gas}\times\frac{1kg}{1000g}=12.09kg\times 0.85=10.28kg\ CE$$

High

$$\frac{20.4ml\ gas}{\min}\times\frac{1288\min}{year}\times\frac{1lt}{1000ml}\times\frac{739g}{1lt\ gas}\times\frac{1kg}{1000g}=19.42kg\times 0.85=16.50kg\ CE$$

Turfgrass water use and evapotransporation (ET) rates are well established (Kenna, 2006), and vary among turfgrass species and ecoregions. The rates for turfgrasses range from 3.0 – 8.0 mm d^{-1} for water use, and from 3.0 – 12.0 mm d^{-1} for ET (Beard, 1973; Kenna, 2006). In general, BMPs suggest irrigating turfgrass when rainfall rates are less than that of ET (Thurn et al., 1994; Osmond and Bruneau, 1999; McKindly, 2005; Trenholm et al., 2002). The majority of homeowners use hose end sprinklers (Powell and Witt, 2002). The CE conversion for hand moved sprinklers is 16.3 kg CE $ha^{-1}yr^{-1}$ (Lal, 2004b). The average size lawn consumes 1.3 kg CE $lawn^{-1}$ yr^{-1}(Eq. 2.6).

16.3 kg x 0.08 ha = 1.3 kg CE……………………………………………**Equation 2.6**

2.4 Results and discussions

2.4.1 Minimal Input management

The MI lawns, comprising of 40 million homes, are defined as mowing once a week without irrigation, fertilizer, or pesticide use (Augustin 2007). The net SOC sequestration model for MI is based on gross SOC minus the HCC.

The gross SOC sequestration rate is 80.0 kg SOC $lawn^{-1}$ yr^{-1} (Table 2.2 and 2.3). The CE for mowing is used to estimate the total HCC for MI. The CE for mowing is 10.3 – 16.5 kg lawn^{-1} yr^{-1} as stated in the HCC section. The average MI lawn accumulates 80.0 kg SOC lawn^{-1} yr^{-1} and HCC of 10.3 – 16.5 kg CE lawn^{-1} yr^{-1}. Thus, total Net SOC sequestration rate is 63.5 – 69.7 kg C lawn^{-1} yr^{-1}.

2.4.2 Do-It-Yourself management

The DIY rate of SOC sequestration by NPP and pervious SOC sequestration rate studies is 80.0 kg lawn^{-1} yr^{-1} (Table 2.2 and 2.3). The SOC sequestration rate from N fertilization is based on 2.63x 10^{5} Mg of N yr^{-1} applied to all DIY lawns divided by 30 million lawns. DIY lawns apply approximately 109.5 kg ha^{-1} yr^{-1} N and an estimated 9,800 kg biomass ha^{-1} yr^{-1} (Graber and Ream, 1931; Harrison, 1934; Lovvorn, 1945; Juska et al., 1955; Beaty et al., 1960; Madison, 1961; Sullivan, 1961; Juska and Hanson, 1968; Warnes and Newell, 1968). This is 7,800 kg ha^{-1} yr^{-1} more than unfertilized lawns (Graber and Ream, 1931; Harrison, 1934; Lovvorn, 1945; Juska et al., 1955; Beaty et al., 1960; Madison, 1961; Sullivan, 1961; Juska and Hanson, 1968; Warnes and Newell, 1968). After accounting for humification efficacy, each DIY lawn accumulates 62.4 kg SOC lawn^{-1} yr^{-1} from fertilization (Eq. 2.7).

<u>DIY Fertilizer SOC Sequestration</u>

$$7{,}800\ kg \times 0.10 = 780\ kg\ biomass$$
$$780\ kg \times 0.08 = 62.4\ kg\ C$$
……………………………………………..………..**Equation 2.7**

Only 10-15% (3 – 4.5 million) of DIY lawns are irrigated (NASS, 2002; 2004). Irrigation can sequester an additional 50 – 100 kg C ha^{-1} yr^{-1} (Lal, 2004b). Therefore, the total for 3 – 4.5 million homes is 12, 000 – 36,000 Mg C yr^{-1}. This total is divided by 30 million home lawns in the DIY category to determine the average on a per lawn basis. The average for each home lawn is derived from the total DIY irrigation SOC sequestration rate. The SOC sequestration rate for irrigation in DIY lawns averages 0.4 – 1.2 kg C $lawn^{-1}$ yr^{-1}(Eq. 2.8).

DIY Low Irrigation SOC Sequestration

$$50\ kg \times 240{,}000\, ha = 12{,}000{,}000\ kg\ C$$
$$12{,}000{,}000\ kg \div 30\ Million = 0.4\ kg\ C$$

……………………………………..**Equation 2.8**

DIY High Irrigation SOC Sequestration

$$100\ kg \times 360{,}000 ha = 36{,}000{,}000\ kg\ C$$
$$36{,}000{,}000\ kg \times 0.08 = 1.2\ kg\ C$$

The CE for mowing, irrigation, and applying fertilizers and pesticides are summed to obtain the total HCC for DIY. The CE for mowing is 10.3 – 16.5 kg $lawn^{-1}$ yr^{-1} (refer to HCC section). The CE for Irrigation is an average of the 10 -15% of households which irrigate. The CE for hand moved sprinklers (16.3 kg CE ha^{-1} yr^{-1}) is multiplied over the 3 – 4.5 million DIY home lawns. This total is divided by 30 million DIY lawns for an average of 0.1 – 0.2 kg CE $lawn^{-1}$ yr^{-1}. Fertilizer use for DIY lawns in the U.S. is 9.07 x 10^5 Mg of fertilizer sold to the DIY category on a yearly basis (The Scotts Miracle-Gro Company, 2006). Typical lawn fertilizer analysis by weight is 29% nitrogen (N), 3% phosphorus (P_2O_5), and 4% potassium (K_2O) (The Scotts Miracle-Gro Company, 2006). This equals 2.63x 10^5 Mg of N yr^{-1}, 2.70 x 10^4 Mg of P_2O_5 yr^{-1}, and 3.60 x 10^4 Mg of K_2O yr^{-1}. The CE conversion for fertilizer is based on energy for production, transportation, storage, and transfer (Lal, 2004b). The CE conversion is 0.9 – 1.8 kg CE kg^{-1} N, CE of 0.1 – 0.3 kg CE kg^{-1} of P_2O_5, and CE of 0.1 – 0.2 kg CE per kg^{-1} of K_2O (Lal, 2004b). The amount of N, P_2O_5, and K_2O is multiplied by the appropriate fertilizer component CE for a total of 8.1 – 16.3 kg CE $lawn^{-1}$ yr^{-1}(Eq. 2.9).

DIY Low N

$236,000,000\ kg \times 0.9 = 236,700,000\ kg\ CE$

DIY High N

$236,000,000\ kg \times 0.9 = 424,,800,000\ kg\ CE$

DIY Low P

$27,000,000\ kg \times 0.1 = 2,700,000\ kg\ CE$

DIY High P

$27,000,000\ kg \times 0.3 = 8,100,000\ kg\ CE$

DIY Low K

$36,000,000\ kg \times 0.1 = 3,600,000\ kg\ CE$

DIY High K ………**Equation 2.9**

$36,000,000\ kg \times 0.2 = 7,200,000\ kg\ CE$

DIY Low N-P-K

$243,000,000\ kg \div 30 Million = 8.1 kgCE$

DIY High N-P-K

$440,100,000\ kg \div 30 Million = 14.7 kgCE$

Pesticide use for the lawn and garden category in the U.S. is estimated at 11,800 Mg herbicides and 2,800 Mg insecticides (USEPA, 2004). Since this report includes lawns and gardens, the pesticide rate is divided in half, assuming half are garden pesticides and half are lawn pesticides. Therefore, lawn herbicides are estimated at 5,900 Mg yr^{-1} and pesticides at 1,400 Mg yr^{-1}. The CE conversion for pesticide active ingredients is based on energy required for production, formulation, packaging, and transport (Lal, 2004b). Thus, CE conversions for these pesticides are 1.7 – 12.6 kg CE kg^{-1} herbicide and 1.2 – 8.1 kg CE kg^{-1} insecticide. The average CE for pesticides is 0.3 – 2.1 kg CE lawn^{-1} yr^{-1}(Eq. 2.10).

DIY Low Herbicide

$5.900{,}000\ kg \times 1.7 = 10{,}030{,}000\ kg\ CE$

DIY Low Insecticide

$1{,}400{,}000\ kg \times 1.2 = 1{,}680{,}000\ kg\ CE$

DIY Low Pesticide

$11{,}710{,}000\ kg \div 40\,Million\ = 0.3\ kg\ CE$

DIY High Herbicide

$5{,}900{,}000\ kg \times 12.6 = 74{,}340{,}000\ kg\ CE$

DIY High Insecticide

$1{,}400{,}000\ kg \times 8.1 = 11{,}340{,}000\ kg\ CE$

DIY High Pesticide ……………**Equation 2.10**

$85{,}680{,}000\ kg \div 40\ Million = 2.1\ kg\ CE$

Therefore, the net SOC sequestration rate is calculated by subtracting HCC from gross SOC accumulation. The gross SOC sequestration for the average DIY lawn is 142.8 – 143.6 kg C lawn^{-1} yr^{-1}, with a HCC of 18.8 – 35.1 kg CE lawn^{-1} yr^{-1}. Thus, the total net SOC sequestration rate is 107.7 – 124.8 kg C lawn^{-1} yr^{-1}.

2.4.3 Best Management Practices

Homes following BMPs are comprised of 10 million lawns using a lawn care service or homes using multiple fertilizer applications (Augustin, 2007). Lawn care services adopt university and industry-standard BMPs as a management program.

This program is defined as mowing once per week, fertilizing four times a year with pest prevention, and irrigating regularly when rainfall is insufficient for healthy turfgrass growth (Thurn et al., 1994; Reicher and Throssell, 1998; Osmond and Bruneau, 1999; Carrow et al., 2001; Sartain, 2000; Trenholm et al., 2002; Rieke and Lyman, 2002; Heckman and Murphy, 2003; Fipps et al., 2005; Landschoot, 2005; McKinley, 2005; Street and White, 2006; Louisiana State University, 2008). The net SOC sequestration model for BMPs is also derived by subtracting the HCC from the gross SOC sequestration rate.

The rate of SOC sequestration by NPP and previous SOC sequestration rates from literature is 80.0 kg SOC lawn^{-1}yr^{-1} (Table 2.2 and 2.3). The rate of SOC sequestration through fertilization and irrigation is calculated for the BMPs lawns based on university and industry-standards for fertilizing turfgrass 147.0 – 250.0 kg N ha^{-1} yr^{-1} or 11.8 – 20.0 kg N lawn^{-1} yr $^{-1}$ (Thurn et al., 1994; Reicher and Throssell, 1998; Osmond and Bruneau, 1999; Sartain, 2000; Carrow et al., 2001; Lyman, 2002; Trenholm et al., 2002; Heckman and Murphy, 2003; University of Florida, 2004; Fipps et al., 2005; Landschoot, 2005; McKinley, 2005; Street and White, 2006; Louisiana State University, 2008). This range is based on regional area and species type variations. Fertilizer application produces 7,800 – 9,800 kg more biomass ha^{-1} yr^{-1} than unfertilized grass (Graber and Ream, 1931; Harrison, 1934; Lovvorn, 1945; Juska et al., 1955; Beaty et al., 1960; Madison, 1961; Sullivan, 1961; Juska and

Hanson, 1968; Warnes and Newell, 1968). Accounting for 10% humification efficiency, SOC sequestered through N fertilization is 62.4 – 78.4 kg C lawn^{-1} yr^{-1} (Eq. 2.11) The SOC sequestered from irrigation is calculated at 4.0 – 8.0 kg C lawn^{-1} yr^{-1} (Eq. 2.12)

BMPs Low Fertilizer SOC Sequestration

$$7{,}800\ kg \times 0.10 = 780\ kg\ biomass$$

$$780\ kg \times 0.08 = 62.4\ kg\ C$$

…………………………….**Equation 2.11**

BMPs High Fertilizer SOC Sequestration

$$9{,}800\ kg \times 0.10 = 980\ kg\ biomass$$

$$980\ kg \times 0.08 = 78.4\ kg\ C$$

BMPs Low Irrigation SOC Sequestration

$$50\ kg \times 0.08 = 4.0\ kg\ C$$

………………… ………..**Equation 2.12**

BMPs High Irrigation SOC Sequestration

$$100\ kg \times 0.08 = 8.0\ kg\ C$$

The CE for mowing, irrigation, fertilizer and pesticide applications is summed to compute the total HCC for BMPs. The HCC is 10.3 -16.5 kg CE lawn^{-1} yr^{-1} for mowing (refer to the HCC section). Irrigation use is assumed for all BMPs lawns. The total amount of land under irrigation for BMPs of 0.8 Mha was multiplied by the hand moved sprinkler conversion of 16.3 kg CE ha^{-1} yr^{-1} (Lal, 2004b). BMPs lawns use 1.3 kg CE lawn^{-1} yr^{-1} for irrigation. Fertilizer use as modeled from university and industry-standards is based on applying 11.8 – 20.0 kg N lawn^{-1} yr^{-1} with a common fertilizer analysis ratio of 5-1-2. Therefore, P_2O_5 is applied at 2.4 – 4.0 kg lawn^{-1} yr $^{-1}$and K_2O is applied at 4.8 – 8.0 kg lawn yr $^{-1}$. The CE conversion is 0.9 – 1.8 kg CE kg^{-1} N, CE of 0.1- 0.3 kg CE kg^{-1} of P_2O_5, and CE of 0.1 – 0.2 kg CE per kg^{-1} of K_2O (Lal, 2004b). The amount of N, P_2O_5, and K_2O is multiplied by the appropriate fertilizer component CE for a total of 11.3 – 38.8 kg CE lawn^{-1} yr $^{-1}$ for fertilizer use (Eq. 2.13).

BMPs Low N	**BMPs High N**	
$11.8kg \times 0.9 = 10.62\ kg\ CE$	$20.0\ kg \times 1.8 = 36.0\ kg\ CE$	
BMPs Low P	**BMPs High P**	
$2.4\ kg \times 0.1 = 0.24\ kg\ CE$	$4.7kg \times 0.3 = 1.4\ kg\ CE$	
BMPs Low K	**BMPs High K**	……………**Equation 2.13**
$4.8\ kg \times 0.1 = 0.48\ kg\ CE$	$8.0\ kg \times 0.2 = 1.6\ kg\ CE$	
BMPs Low N-P-K	**BMPs High N-P-K**	
$10.62 + 0.24 + 0.48 = 11.3\ kg\ CE$	$36.0 + 1.2 + 1.6 = 38.8\ kg\ CE$	

Pesticide use for BMPs is modeled on the basis of one application for each of pre-emergence herbicide, post-emergence herbicide, and insect control per year (McKinley, 2005; Louisiana State University, 2008). All pesticide controls are based on common granular fertilizer plus pest control combination product using percent active ingredient of each pesticide (Scotts Training Institute, 2007). Common lawn pesticide active ingredient rates are used to calculate pesticide use. The pre-emergence control involves use of pendimethalin at a rate of 1.77 kg ha^{-1} yr^{-1} (0.14 kg lawn^{-1}). The post-emergence control involves a combination of 2,4-

dichlorophenoxyyacetic acid (2,4-D) at 1.69 kg ha^{-1} yr^{-1} (0.14 kg lawn^{-1}) and Mecoprop-P (MCPP-p) at 0.85 kg ha^{-1} yr^{-1} (0.07 kg lawn^{-1}). Insect control involves the insecticide bifenthrin at 0.09 kg ha^{-1} yr^{-1} (0.01 kg lawn^{-1}). The CE conversion is 1.70 – 12.60 kg CE kg^{-1} herbicide and 1.2 – 8.1 kg CE kg^{-1} insecticide (Lal, 2004b). The total amount of each pesticide is multiplied by the appropriate pesticide CE for a total of 0.6 – 4.48 kg CE lawn^{-1} yr^{-1}(Eq. 2.14).

BMPs Low Herbicide	**BMPs High Herbicide**
$0.35\ kg \times 1.7 = 0.6\ kg\ CE$	$0.35\ kg \times 12.6 = 4.4\ kg\ CE$
BMPs Low Insecticide	**BMPs High Insecticide**…………**Equation 2.14**
$0.01\ kg \times 1.2 = 0.01\ kg\ CE$	$0.01\ kg \times 8.1 = 0.081\ kg\ CE$
BMPs Low Pesticide	**BMPs High Pesticide**
$0.6 + 0.01 = 0.6\ kg\ CE$	$4.4 + 0.081 = 4.48 kg\ CE$

Net SOC sequestration rates are calculated by subtracting HCC from gross SOC sequestration. The average BMP lawn has a gross SOC sequestration rate of 146.4 – 166.4 kg C lawn^{-1} yr^{-1}, and HCC of 24.6 – 61.9 kg CE lawn^{-1} yr^{-1}. Thus, the total net SOC sequestration rate is 84.5 – 141.8 kg C lawn^{-1} yr^{-1}.

2.5 Conclusions

Model predictions of SOC accumulation from NPP compare well with those from grassland and turfgrass SOC sequestration rates in published data. This suggests that SOC accumulation rates are similar to national average values for other land uses. Applying fertilizer and irrigating based on recommendations can increase SOC sequestration rates by increasing plant biomass and the total amount of humification. Home lawns sequester an estimated 0.8 – 1.7 Mg C ha^{-1} yr^{-1}. This rate is greater than average U.S. cropland at 0.3 Mg C ha^{-1} yr^{-1} (Lal and Follett, 2009; Potter et al., 2009). Home lawn C sequestration rates also fall in the same range as world grasslands at 0.6 -1.9 Mg C ha^{-1} yr^{-1} (Bruce et al., 1999).

This model is a simple large scale evaluation of the net SOC sequestration potential of existing home lawns. The scope of the model could be further broadened to account for the soil flux of GHG as result of lawn management practices and soil conditions. The primary GHG soil emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) are highly impacted by soil conditions (Maggiotto et al., 2000; Kaye et al., 2005; Khan et al., 2007; Smith et al,. 2007). CO_2 represents over 98% of the soil GHG flux and is accounted for by NPP estimates in the basic model (Phillips et al., 2009). Emissions of CH_4 are attributed to anaerobic fermentation of organic matter under conditions typical of flooded rice paddies or swamps, but not of typical home lawn ecosystem conditions. Normal well-drained soils are a sink for CH_4 (Jansens et al., 2009; Phillips et al., 2009). Soil emissions of N_2O are <1% of the GHG soil flux and result from soil microbial activity (Kaye et al., 2005; Phillips et al., 2009). Soil N_2O emissions are enhanced under saturated soil conditions (Eichner, 1990; Smith et al., 2007). The average soil N_2O flux is comprised of 65 – 77% background emissions and 23 – 35% fertilizer induced emissions (Snyder et al., 2007). Significant potential exists for the mitigation of these GHG fluxes from soils by management practices according to the Intergovernmental Panel on Climate Change (Smith et al., 2007). Although this model did not account for CH_4 and N_2O, future modeling scenarios should consider inclusion of soil GHG when dictated by specific climate, soil conditions or management practices known to greatly influence GHG fluxes (Neeta et al., 2008; Raciti et al., 2008; Groffman et al., 2009; Lorenz and Lal, 2009b).

Validation through long term field sampling of SOC is needed to determine the extent and limits to which urban lawn soils can sequester carbon. Further research will increase the precision of the model and allow it to be developed for specific climates, soil conditions, and lawn management practices.

	MI	DIY	BMPs
SOC	80.0	80.0	80.0
Fertilizer SOC	0	62.4	62.4 – 78.4
Irrigation SOC	0	0.4 – 1.2	4.00 – 8.00
Gross Soil Organic Carbon	80.0	142.8 – 143.6	146.4 – 166.4
Mowing HCC	10.3 – 16.5	10.3 – 16.5	10.3 – 16.5
Irrigation HCC	0	0.1 – 0.2	1.30
Fertilizer HCC	0	8.1 – 16.3	11.3 – 38.8
Pesticide HCC	0	0.3 – 2.1	0.6 – 4.5
Gross Hidden Carbon Costs	10.3 – 16.5	18.8 – 35.1	23.5 – 61.1
Total Net Sequestration lawn^{-1}	63.5 – 69.7	107.7 – 124.8	85.3 – 142.9

Table 2.4. Annual net soil organic carbon sequestration rate in kg C lawn^{-1} yr^{-1}.

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CHAPTER 3

MODELING TREE, SHRUB, AND LAWN CARBON SEQUESTRATION IN THE TYPICAL US RESIDENTIAL YARD

3.1 Abstract

Urban development and the role of terrestrial carbon sequestration are issues of increasing interest. The first objective of this model is to document the typical urban landscape in terms of lawn area, number of trees and shrubs, area of landscape and garden beds, hard surfaces, and buildings. The second objective is to estimate the annual rate of carbon (C) sequestration of the residential landscape based on the percentage of lawns, trees, and shrubs. Urbanized land occupies approximately 40.6 million hectares (Mha) with an average of 41% of this land under residential use. Tree, shrub, and lawn C sequestration rates were estimated based on the typical US residential lot size of 2,000 m^2. A typical US home is 93 m^2 with a 2-car garage or carport size of 38 m^2 and a deck or patio of 38 m^2. The house is generally sited in the middle of the lot, with a driveway size of 168 m^2 and a sidewalk size of 122 m^2 along the front of the lot. This leaves a landscape area of 1,541 m^2. Two landscape regimes were modeled. The first model had a minimal landscape with one landscape bed in the front of the house 13 m long containing 5 – 10 shrubs approximately 0.6 – 1.2 m in length and width, 2 trees, and a minimal managed lawn. The second model had a

maximum landscape with several landscape beds 43 m long surrounding the perimeter of the house containing 17 – 35 shrubs approximately 0.6 – 1.2 meters in length and width, 6 trees, and a highly maintained lawn. The total or gross C sequestration rate for trees is 3.4 – 5.9 kg C $tree^{-1}$ $yr^{-1}$and 0.07 – 0.23 kg C $shrub^{-1}$ yr^{-1}. Lawn sequestration rate is 794 – 1,786 kg C ha^{-1} yr^{-1} based on prior models. A minimal landscaped yard sequesters 111.5 – 139.4 kg C $yard^{-1}$ yr^{-1}. Based on the model, approximately 7.4% is sequestered by trees, 1.1% by shrubs, and 91.5% by the lawn. A maximum landscape yard sequesters 110.9 – 262.8 kg C $yard^{-1}$ yr^{-1} with 14.9% from trees, 2.6% by shrubs, and 82.5% by the lawn.

3.2 Introduction

As urban development increases, carbon dioxide (CO_2) and terrestrial carbon (C) sequestration are areas of increasing interest. Urbanized land occupies 3.5% to 4.9% of U.S. land with approximately 40.6 million hectares (Mha) (NAR, 2001; Nowak et al., 2001). An average of 41% of urban area is under residential use (Nowak et al., 1996; 2001). Thus, residential land needs to be evaluated for its influences on the C cycle.

Atmospheric CO_2 is photosynthesized and stored as plant biomass. Some of this plant biomass C is humified and stored for a long time in the soil as humus or soil organic carbon (SOC). The SOC pool is increased when humus content increases and gains of biomass C into the soil equal or exceed losses (Bruce et al., 1999). The net C gains change over time as plants and soils change with input, senescence, and decay. Land use and plant and soil management practices influence the rate of C sequestration. Estimated C density in U.S. urban soils is 7.7 ± 0.2 kg m^{-2} (Pouyat et al., 2006).

Trees and shrubs remove significant amounts of air pollutants and their presence is important to improving environmental air quality. The pollution removed includes ozone (O_3), particulate matter less than ten microns (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) (USDA, 2006). Biota are estimated to remove 711 Tg (Teragrams = 1 million metric tons) of pollutants from the air in the US alone (Nowak et al. 2006). Storage of C and gross C sequestration by urban trees in U.S. cities ranges from1.2 Tg in New York City to 19.3 Tg in Jersey City (Nowak and Crane 2002). Gross C sequestration for the U.S. is estimated at 22.8 Tg C (Nowak and Crane, 2002). The amount of C in individual trees has been estimated at 1.4 – 54.5 kg C $tree^{-1}$ yr^{-1} (Nowak and Crane, 2002; England, 2006).

Grass lawns in the U.S. occupy 6.4 Mha with an average home lawn size of 0.08 ha (Vinlove, 1995; NAR, 2001; Zirkle et al., 2010). Lawns have the potential to sequester C at rates as high as 1.0 Mg C ha^{-1} yr^{-1} (Gebhart et al. 1994; Contant et al. 2001; Qian and Follett, 2002; 2009). A net C sequestration rate in household lawns is 793.8 – 1,786 kg C ha^{-1} yr^{-1} (Chapter 2), based on low to high management regimes and considering hidden C costs (HCC) of mowing, irrigation, fertilizer, and pesticide applications.

While home lawns, along with trees and shrubs have potential to sequester C, research data on SOC dynamics for residential yards is scanty. Thus, the objective of this study was to predict the rate of terrestrial C sequestration by trees and shrubs, including the SOC sequestration in soil under household lawns in the U.S. Specific objectives of this study were to: (i) document the typical urban landscape in terms of lawn area, number of trees and shrubs, area of landscape and garden beds, hard surface areas, and building areas, (ii) estimate the annual rate of C sequestration of the typical home landscape, including the percentage lawn, trees, and shrubs, to contribute C sequestration, and (iii) evaluate the range of annual U.S. C sequestration rates including that by trees, shrubs, and lawns.

3.3 Materials and methods

3.3.1 Residential landscape area

This model estimated the SOC sequestration under turfgrass and C stock in tree and shrub biomass of a typical residential yard in the US. Available data from literature was used to configure and model C sequestration rates for a typical residential home lot.

The rate of C sequestration over time can be measured directly and indirectly (Smith et al., 1993; Bruce et al., 1999; Rickman et al., 2001; Smith et al., 2008). Mathematical C sequestration modeling is well developed and used to predict C cycles under various environmental and regional scales (Smith et al., 1993; Bruce et al., 1999; Lal, 2004; Post, 2004; Smith et al., 2008). Modeling, based on life cycle analysis, was used in this study to estimate C sequestration potential for residential lots over a national scale. Net C sequestration was comprised of net lawn SOC sequestration plus that sequestered by tree and shrub biomass C.

The average U.S. single family residential home lot of 2,000 m^2 is comprised of an average house size of 93 m^2 (USCB, 2008). The majority of homes have a 2-car garage or carport with a size of 38 m^2 or (USCB, 2008). A deck or patio is common for the average residential home and is 38 m^2. The house is assumed to be in the middle of the lot with a driveway size of 168 m^2 and a sidewalk size of 122 m^2 . The remaining 1,541 m^2 is landscape area.

Since residential home landscapes differ in landscape-bed size and plant species diversity, a model was developed using a range of landscape-bed sizes. The minimum is based on a home with one landscape-bed 13 linear m long in the front of the house (Figure 3.1). The bed length is determined from a house 40 m along the front of the house and leaving 1/3 open for a walkway and entryway. The maximum includes a home with 43 linear m of landscape-beds surrounding the perimeter of the house (Figure 3.2). This bed length was also determined by leaving 1/3 open for deck, garage, walkways, and entry ways. The range of possible landscape-beds is 13 – 43 linear m.

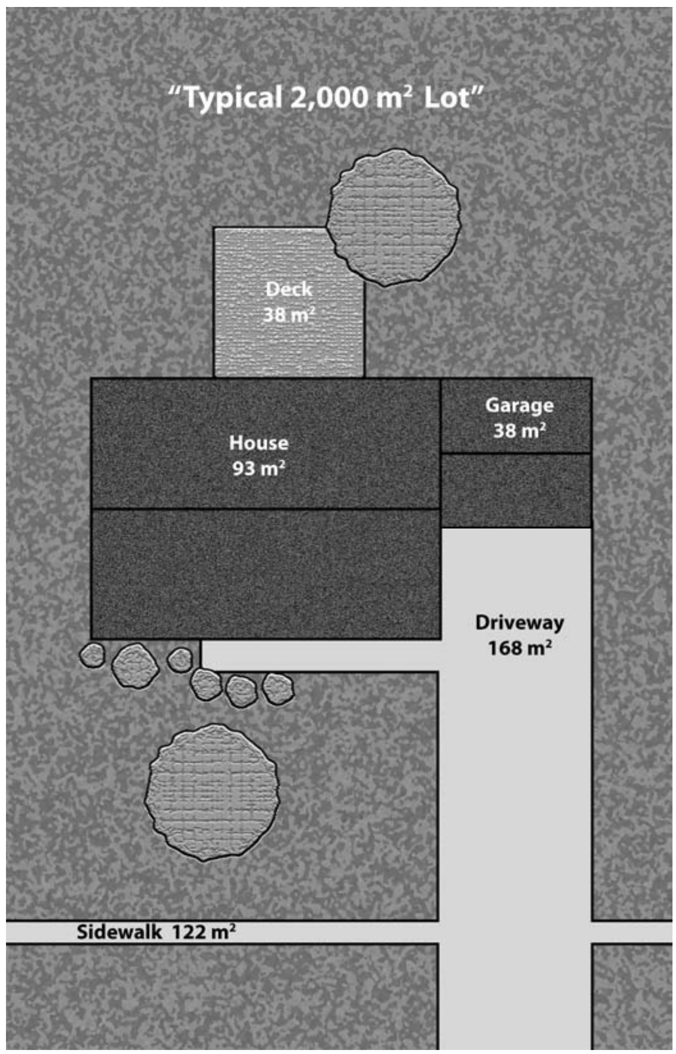

Figure 3.1. Minimal Landscape lot

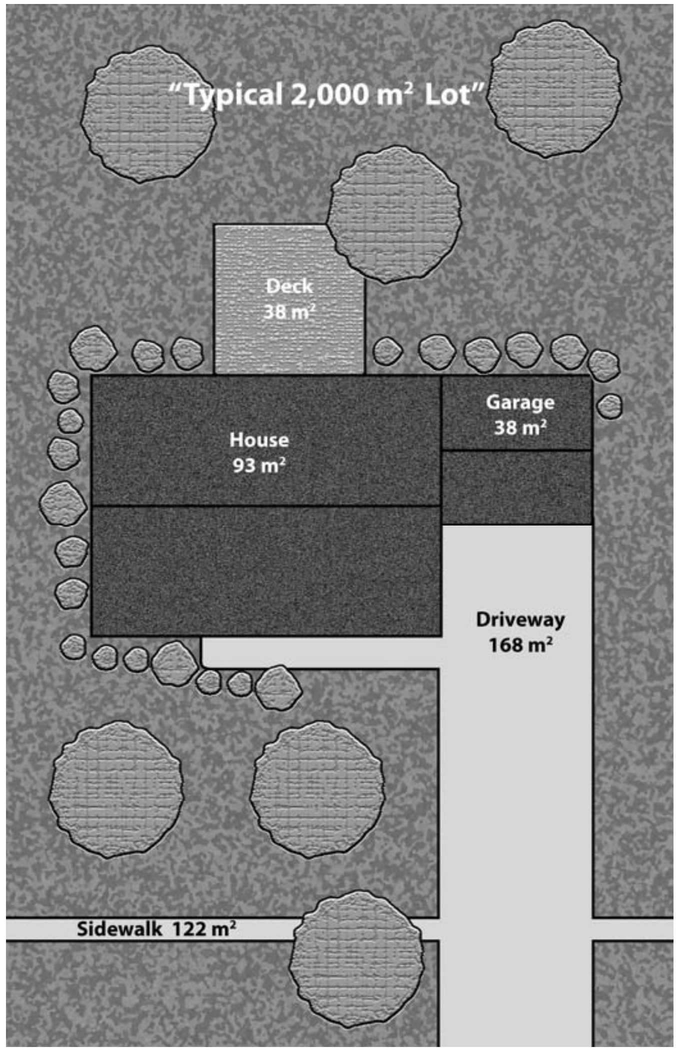

Figure 3.2. Maximum Landscape Lot

A large number of tree species and sizes occur in a residential landscape. Therefore, a range in the average tree count yard^{-1} was derived from the available literature. The density ranges from 2 – 6 trees yard^{-1} (Simpson and McPherson, 1998; Martin et al., 2003; Swiecki and Bernhardt, 2006; Casey Trees, 2008). Table 3.1 represents the average tree canopy diameter ranging from 8 – 11 m and was determined from the 10 most common tree species grown in the U.S. (Little, 1979; Dirr, 1998). The average tree canopy area of 50 – 133 m^2 was calculated from the average tree canopy diameter.

Tree Species	**Minimal Canopy Diameter (m)**	**Maximum Canopy Diameter (m)**
Red Maple (*Acer rubrum*)	7	9
Loblolly Pine (*Pinus taeda*)	9	11
Sweetgum (*Liquidambar styraciflua*)	11	15
Douglas Fir (*Pseudotsuga menziesii*)	5	8
Quaking Aspen (*Populus tremuloides*)	6	9
Sugar Maple (*Acer saccharum*)	12	15
Balsam Fir (*Abies balsamea*)	6	8
Flowering Dogwood (*Cornus florida*)	5	6
Lodgepole Pine (*Pinus contorta*)	3	4
White Oak (*Quercus alba*)	18	24
Average	**8**	**11**

Table 3.1 Top ten tree species in the U.S. and canopy sizes in meters

Shrubs within these beds also range in plant size and species diversity. Spacing of shrubs is dependent on species and personal preference of density. To keep within typical home residential landscape planting practices, an average range of shrubs $yard^{-1}$ was determined. Shrubs were assumed to be between 0.6 – 1.2 m in length and width, as well as spaced 0.6 – 1.2 m apart. The minimum landscape bed of 13 m in length contains 5 – 10 shrubs. The maximum landscape bed is 43 m long and contains 17– 35 shrubs. Thus, the range is from 5 – 35 shrubs $yard^{-1}$.

Lawn area was determined by subtracting the amount of canopy area from the trees and shrubs. It was assumed the area of land under trees and shrubs does not receive adequate sunlight for turfgrass growth.

3.3.2 Tree, shrub, and lawn C sequestration

Average C stored in above and belowground biomass of trees and shrubs was compiled from the literature. Total, or gross, C sequestration for trees and shrubs was estimated based on individual tree and shrub count.

Total net tree C sequestration ranged from 3.4 – 5.9 kg C $tree^{-1}$ yr^{-1}(Nowak and Crane, 2002) (Table 3.2). This range was calculated using equations reported in the literature (Nowak, 1994; Nowak et al., 2001). Specific cities shown in Table 3.2 are included in the regions with the highest C storage and sequestration rates within the

U.S. (Nowak and Crane, 2002). Therefore, the net C rates for these cities fall within the estimated range for the U.S. This data on above-ground biomass was converted to whole tree biomass based on a root:shoot ratio of 0.26 (Cairns et al., 1997).

City	Net C ha^{-1} (kg)	Trees ha^{-1}	Net C $tree^{-1}$ (kg)
Atlanta, GA	940	276	3.41
Baltimore, MD	520	136	3.82
Syracuse, NY	540	137	3.94
Boston, MA	490	83	5.90
New York, NY	260	65	4.00
Philadelphia, PA	310	62	5.00
Jersey City, NJ	150	36	4.17

Table 3.2 Estimated annual net C storage $tree^{-1}$ yr^{-1} (from Nowak and Crane, 2002)

The tree C sequestration rate calculated from Equation 3.1 indicates the minimum number of trees sequestered 6.8 – 11.8 kg C $yard^{-1}$ yr^{-1}. The maximum number of trees sequestered 20.4 – 35.4 kg C $yard^{-1}$ yr^{-1}. Thus, total C sequestered by trees ranges from 6.8 to 35.4 kg C $yard^{-1}$ yr^{-1}.

<u>Net Tree C sequestration rate</u>

Minimum tree net C sequestration = 3.4 kg C x number of trees

……..**Equation 3.1**

Maximum tree net C sequestration = 5.9 kg C x number of trees

The rate of C sequestration in shrubs was calculated by taking the percentage of canopy area covered by shrubs compared to that of trees. Shrubs 0.6 – 1.2 m wide have a canopy area of between 0.9 – 3.8 m^2. Shrubs had approximately 0.02 – 0.04% area and sequestration rate to that of trees. Thus, the C sequestration rate is 0.07 – 0.23 kg C $shrub^{-1}$. The shrub C sequestration rate was calculated from Eq. 3.2 and indicates the minimum number of shrubs sequestered 0.4 – 2.4 kg C $yard^{-1}$ yr^{-1}. The maximum number of shrubs sequestered 1.2 – 8.4 kg $yard^{-1}$ yr^{-1}. Thus, the total C sequestered by shrubs ranged from 0.4 to 8.4 kg C $yard^{-1}$ yr^{-1}.

Net Shrub C Sequestration rate

Minimum shrub net C sequestration = 0.07 kg C x number of shrubs

…...**Equation 3.2**

Maximum shrub net C sequestration = 0.23 kg C x number of shrubs

Lawn C sequestration rates were calculated by subtracting the hidden carbon costs (HCC) of mowing, irrigation, fertilization, and pesticide use from gross SOC sequestration (Chapter 2). Gross SOC sequestration involved a combination of SOC sequestration rates and gross primary productivity data available from the literature. The HCC were calculated by converting energy use requirements for lawn management practices into C equivalents. The prior chapter has shown that home lawns sequester SOC at a rate of 794 – 1,786 kg C ha^{-1} yr^{-1}. Minimal managed lawns are mowed once a week without any irrigation, fertilizer, or pest control. Technical potential of C sequestration of these lawns is 794 – 871 kg C ha^{-1} yr^{-1}. The rate of C sequestration by the lawns managed at the maximum maintenance level is 1,066 – 1,786 kg C ha^{-1} yr^{-1}, and includes mowing, irrigation, fertilizer and pesticide applications.

After subtracting the amount of tree and shrub canopy area, yards in the minimal landscape regime have a lawn area of 1,313 – 1,437 m^2. The lawn C sequestration rate under minimal management is 104.3 – 125.2 kg C $lawn^{-1}$ yr^{-1} which is derived from taking the percentage from one hectare of lawn. The maximum landscape has a lawn area of 835 – 1,226 m^2 and a C sequestration rate of 89.3 – 219.0 kg C $lawn^{-1}$ yr^{-1}.

3.4 Results and discussion

The C sequestration rates for individual tree, shrub, and lawn areas were totaled to attain the gross C sequestration rate for a typical residential landscape in the U.S. Tree count was based on data available from literature. The area of landscape beds and shrub canopy determines the total amount of shrubs. Two different landscape regimes are configured to provide a range of minimal to maximum amount of tree and shrub count $yard^{-1}$ yr^{-1}. The minimal residential landscape has a landscape-bed 13 m in length with 2 trees and 5 – 10 shrubs. The maximum residential landscape has a landscape bed 43 m long with 6 trees and 17 – 35 shrubs.

A minimal landscaped yard sequesters 111.5 – 139.4 kg C $yard^{-1}$ yr^{-1}. An average of 7.4% is sequestered by trees, 1.1% by shrubs, and 91.5% by the lawn (Table 3.3). The maximum landscaped yard sequesters 110.9 – 262.8 kg C $yard^{-1}$ yr^{-1} and an average of 14.9% by trees, 2.6% by shrubs, and 82.5% by the lawn (Table 3.3).

Parameter	Trees	Shrubs	Lawns
Minimum C sequestered (kg)	6.8 – 11.8 (9.3)	0.4 – 2.4 (1.4)	104.3 – 125.2 (114.8)
Percent C in each category	7.4	1.1	91.5
Maximum C sequestered (kg)	20.4 – 35.4 (27.9)	1.2 – 8.4 (3.5)	89.3 – 219.0 (154.2)
Percent C in each category	14.9	2.6	82.5

Table 3.3 Annual net carbon sequestration rate $yard^{-1}$ yr^{-1}

There are approximately 80 million U.S. single family detached homes (NGA, 2004; Augustin 2007). The total potential range for the U.S. is 4.6 – 10.9 Tg C yr^{-1} (0.7 – 1.7 Mg C ha^{-1} yr^{-1}). The amount of trees and shrubs for U.S. yards ranges from 0.4 – 2.8 billion shrubs and 160 – 480 million trees. These ranges are calculated from all yards being maintained as a minimal to a maximum landscape. Since yards are managed at various maintenance regimes, this range should fall within the actual range for the U.S.

The tree C sequestration rates were based on estimations from cities with the most tree cover, with most occurring in the northeastern U.S. Actual C sequestration rates will vary among tree and shrub species (Woodbury et al., 2007). A report from the USDA (2006) states out of the 109 species studied, the tulip tree (*Liriodendron tulipifera*) is estimated to sequester the most C in Washington D.C., while the American sycamore (*Platanus occidentalis*) sequesters the least amount of C annually. The C sequestration rates will also vary based on tree and shrub size and diameter. As trees and shrubs grow, C content accumulates in the plant tissue. Therefore, larger trees will sequester more C than smaller trees due to the difference in plant tissue. When a tree dies and decays, the stored C is released.

Regional ecosystem conditions and species tolerance will also influence the rate of C sequestration and growth among trees, shrubs, and turfgrass ecosystems (Woodbury et al. 2007; Zirkle et al. 2010). For example, areas in parts of the arid southwest may manage yards using xeriscape. Xeriscaped yards include water-efficient landscaping techniques and drought tolerant plant species (Welch, 1991). These yards typically include little to no turfgrass areas (Welch, 1991).

Another influence on C sequestration is plant species from a residential neighborhood scale. Interactions between residents within a neighborhood can influence the type of species and landscape regime a resident will choose (Jim, 1993). These choices can be driven through observation of what neighbors have done with the landscape or as a result of neighbors' suggestions (Routaboule, 1995).

Other herbaceous plants such as perennials and annuals are found in many residential landscapes. The C balances for these plants were not evaluated as a result of the considerable differences in number of species, plant amount, and maintenance practices when comparing residential yards across the U.S. Jo and McPherson (1995) documented herbaceous plants in residential landscapes retain relatively small amounts of C compared to that in trees and shrubs.

Converting C into CO_2 by multiplying the atomic weight of CO_2 (44) by the atomic weight of C (12), the total technical range is 16.9 – 40.0 Tg CO_2 yr^{-1} for residential yards in the U.S. (2.6 – 6.2 Mg CO_2 ha^{-1} yr^{-1}). The minimal landscape ranges from 408.8 – 511.1 kg CO_2 $yard^{-1}$ yr^{-1}, while the maximum landscape ranges from 406.6 – 963.6 kg CO_2 $yard^{-1}$ yr^{-1}. These conversions do not include the other pollutants which trees, shrubs, and grasses also remove.

The USEPA (2009) documents forest CO_2 uptake at 3,201 kg ha^{-1} yr^{-1}. Lawn CO_2 uptake is calculated at 2,505 – 3,298 kg ha^{-1} yr^{-1} for minimal input (MI) lawns, 4,936 – 5,720 kg ha^{-1} yr^{-1} for do-it-yourself (DIY) lawns, and 3,910 – 6,550 kg ha^{-1} yr^{-1} for lawns maintained at university best management practices (BMPs). Table 3.4 shows a comparison of lawn, landscape, and forest CO_2 uptake.

Parameter	kg CO_2 ha^{-1} yr^{-1}
Minimal Input lawn SOC sequestration	2,910 – 3,194
Do-It-Yourself lawn SOC sequestration	4,936 – 5,720
Best Management Practices lawn SOC sequestration	3,910 – 6,550
Minimal Landscape C stock	2,044 – 2,566
Maximum Landscape C stock	2,033 – 4,818
Forest C stock	3,201

Table 3.4. Comparison of annual lawn, landscape, and forest CO_2 sequestration rates

Most CO_2 uptake of a forest comes from the above ground growth or the wood of the tree (USEPA, 2009). When a forest ecosystem experiences natural tree loss, the CO_2 stored is released back into the atmosphere. In a lawn, the CO_2 is sequestered below ground in the soil. Lawns experience minimal soil disturbances; therefore CO_2 uptake can occur over a long period of time. Loss of CO_2 from a lawn covered soil does occur through soil and plant respiration, but is typically at minimal rates when compared to the amount sequestered.

The BMP lawn management regime sequesters the most CO_2 at the high range compared to the other regimes in this study. This is closely followed by the high end of the Maximum management regime. These applications can increase the amount of net primary productivity and soil organic carbon accumulated each year. With trees and shrubs, fertilizer and irrigation applications may occur, but net primary productivity is usually lower when compared to a grass species.

Residential landscapes and green spaces have various other benefits which improve urban environments. Green plants have a positive impact on moods, can promote health, and relieve stress (Ulrich, 1984; Hull, 1992). Residential landscapes can also increase property values, in turn influencing homeowner's decisions on where to live (Getz et al., 1982; Anderson and Cordell, 1985).

3.5 Conclusions

A practical model is described to estimate the net C sequestration of a typical U.S. residential yard. The typical U.S. yard sequesters 110.9 – 262.8 kg C yard^{-1} yr^{-1} (406.6 – 963.6 kg CO_2 yard^{-1} yr^{-1}) with a total technical potential of 4.6 – 10.9 Tg C yr^{-1} (16.8 – 40.0 Tg CO_2 yr^{-1}) for the U.S.

This model is a large scale evaluation of the C sequestration potential of existing residential yards. It does not include residential yards under xeriscape nor arid-zone yards wherein lawns are not or only marginally used, nor does it include C sequestration by various arid-zone species that might be used in such yards. It also does not include other greenhouse gas emissions from the soil such as methane and nitrous oxide. It also excludes C equivalents for manufacturing of any equipment used for residential landscape management. Validation of this model through field sampling is needed to determine the extent and limits to which residential yards can sequester C. Further research is needed in these areas to increase precision of the model.

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CHAPTER 4

SUMMARY AND FUTURE SUGGESTIONS

4.1 Summary

This study involves a mathematical model based on existing data from literature to identify the potential for carbon sequestration in residential landscapes. It estimated the impact of home lawns, trees, and shrubs on the development of terrestrial and soil carbon (C) dynamics and net C sequestration rates. Home lawns have the potential to enhance soil quality and C sequestration as a result of management regimes and lawn characteristics including perennial plant cover, minimal soil physical disturbance, and a constant addition of biomass through mowing and root growth. Most C uptake of trees and shrubs is from the above ground growth (wood, stems, and leaves).

In Chapter 2, it was shown that home lawns in the U.S. have the potential to sequester soil organic carbon (SOC) under minimal input (MI), Do-It-Yourself (DIY), and Best Management Practices (BMPs) lawn management regimes with the average size lawn of 0.08 ha. Management inputs of fertilizer and irrigation can increase plant biomass and in relation the total amount of SOC sequestration on a yearly basis. The total range for net soil C sequestration was 63.5 – 142.9 kg C lawn^{-1} yr^{-1} with a total technical potential of 0.8 – 1.7 Mg C ha^{-1} yr^{-1}. This rate is similar to that of world grasslands at 0.6 – 1.9 Mg C ha^{-1} yr^{-1} and greater than conventional agriculture at 0.3 Mg C ha^{-1} yr^{-1}.

Chapter 3 combined home lawn C sequestration rates with tree and shrub C sequestration rates based on the landscape of a typical U.S. residential yard. A typical US home was 93 m^2 with a 2-car garage or carport size of 38 m^2, deck or patio of 38 m^2, and a driveway size of 168 m^2 and a sidewalk size of 122 m^2. The remaining 1,541 m^2 was landscape area. Two landscape regimes were modeled. The first model had a minimal landscape with one landscape bed in the front of the house 13 m long containing 5 – 10 shrubs approximately 0.6 to 1.2 m in length and width, 2 trees, and a minimal managed lawn. The second model had a maximum landscape with several landscape beds 43 m long surrounding the perimeter of the house containing 17 – 35 shrubs approximately 0.6 to 1.2 meters in length and width, 6 trees, and highly maintained lawn. Tree C sequestration rates were derived from available literature. Shrub C sequestration rates were estimated at a fraction to that of tree canopy size. Residential yards have the potential to sequester C under minimal and maximum landscapes. A minimal landscaped yard had a C sequestration rate of 111.5 – 139.4 kg C $yard^{-1}$ yr^{-1} with an average of 7.4% by trees, 1.1% by shrubs, and 91.5% by the lawn. The maximum landscaped yard had a C sequestration rate of 110.9 – 262.8 kg C $yard^{-1}$ yr^{-1} with an average of 14.9% from trees, 2.6% by shrubs, and

82.5% by the lawn. The total technical potential of residential yards in the U.S. is 4.6 – 10.9 Tg C yr^{-1}.

A comparison of lawn, landscape, and forest CO_2 in chapter 3 demonstrates that residential lawns and landscapes can sequester CO_2 at an equal or greater amount than a natural forest. Table 4.1 documents the relative land amount and C sequestration rate potential of various land uses in the U.S. On a per hectare basis, residential yards have the potential to sequester greater amounts of C than U.S. forests and croplands. Although residential yards may sequester more C than other lands uses, the amount of land covered by this are is relatively small when compared to the amount of land covered by cropland and forestland in the U.S. (Table 4.1).

Parameter for U.S.	Land Amount (Mha)	Potential C Sequestration (Tg C yr^{-1})	Potential C sequestration rate (kg C ha^{-1} yr^{-1})
Entire U.S.	936	144 – 432	154 – 462
Cropland	157	45 – 98	287 – 625
Residential Yards	7	8 – 11	1219 – 1703
Forestlands	236	25 – 102	105 – 432

* Agricultural CO_2 emissions are 413 Tg yr^{-1} (USEPA, 2004). Residential yards offset approximately 2 – 3% of agricultural admissions.

Table 4.1 U.S. land amount and potential C sequestration rates for different land uses. Entire U.S., cropland, and forestlands amounts and potential C sequestration rates taken from Lal et al. (2003).

The models in this study are estimations built on known homeowner's and maintenance practices, as well as parameter assumptions. The assumptions for the first model are mentioned in detail in chapter 2 and include:

- A standardized lawn size of 0.08 ha
- Mowing with a walk behind mower once per week
- 3 Categories of lawn management practices
    - MI
    - DIY
    - BMPs

The assumptions for the second model are mentioned in more detail in chapter 3 and include:

- A standard residential lot of 2000 m^2
    - House of 93 m^2
    - Garage of 38 m^2
    - Driveway of 168 m^2
    - Deck of 38 m^2
    - Sidewalk of 122 m^2
    - Landscape of 1,541 m^2
- 2 levels of landscape regimes
    - Minimal landscaped yard

- Maximum landscaped yard

The models estimate that residential landscape areas with a lawn, trees, and shrubs may have a significant effect on the C cycle. The influence of these landscapes are unrepresented in global carbon fluxes due to the complexity and variability of urban ecosystems. Therefore, the amount of land and management regimes of residential landscapes should be considered as a major influence on national and global C dynamics.

4.2 Future suggestions

This study presents a broad overview of current literature and estimates of C sequestration rates within a residential landscape. Urban ecosystems including residential landscapes are variable and complex (Pouyat et al,. 2002; 2006; Woodbury et al., 2007). Therefore, there are a few considerations for future research. First, this study did not include the influence of regional soil, environmental, and species tolerance or the extent and limits of C sequestration and growth among trees, shrubs, and turfgrass ecosystems. For validation of the model, long term field soil sampling should be considered in major cities across the U.S. Regionalizing these samples may ameliorate the understanding of regional differences in plant species and C sequestration potential.

Secondly, green plants including trees and shrubs are documented for the ability to remove air pollutants and improve air quality (Nowak et al., 1994; USDA, 2006). The ability and quantity of air pollutant removal by lawns, trees, and shrubs in residential landscapes should be evaluated on a national and global scale. Also, CO_2 is not the only greenhouse gas of concern. CH_4 and N_2O emissions are also on the rise (IPPC, 2007). The sequestration potential of plants and emissions associated with HCC of CH_4 and N_2O were not evaluated in our models. To gain a better understanding of the complete greenhouse gas budget, these gases should be included.

Third, this model was an evaluation of existing lawns and the hidden C costs (HCC) associated with production, transportation, and applications of fertilizer and pesticides, as well as energy required to mow and irrigate. The HCC included in lawn establishment and manufacturing of lawn or landscape equipment, and human labor were not included in these models. Further evaluation of these associations may increase the precision of research in the future.

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