Carbon Sequestration By Home Lawn Turfgrass Development and Maintenance in Diverse Climatic Regions of the United States

Dissertation

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By

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Abstract

As the human population rapidly expands, it has increased urbanization and industrialization globally. Due to this expansion in urbanization, the increased combustion of fossil fuels and land use changes have substantially increased the atmospheric carbon dioxide (CO$_2$) concentration, resulting in numerous environmental concerns, most notably global climate change (GCC). In an attempt to slow the increase in atmospheric CO$_2$ enrichment, researchers are looking at the capacity of world soils to sequester atmospheric carbon (C) and mitigate GCC. The following study quantifies the potential of U.S. home lawn turfgrass soils to sequester soil organic carbon (SOC).

Analyses of turfgrass soils located throughout diverse ecoregions indicate that U.S. home lawns sequester a significant amount of SOC over time. Rates of soil organic carbon sequestration ranged from 0.01% yr$^{-1}$ to 0.70% yr$^{-1}$ depending on location and depth of soils. Majority of lawns sequestered SOC to concentrations of 2-3% to 15 cm depth, however, notably high SOC concentrations were observed in the soils of Minneapolis, MN (5.6%), Wooster, OH (3.4%), Denver, CO (3.2%), and Duluth, MN (3.1). In contrast, notably low SOC concentrations were observed for soils located in Atlanta, GA (1.5%). U.S. soils initially sequestered SOC for an average of 18 years, after which time SOC concentrations stabilized for ~40-50 years before further increasing.

Soil inorganic carbon (SIC) concentrations were also determined. Significant
concentrations of SIC were observed in lawns located in the hot, arid climates of Dallas, TX (2.2%) and Las Vegas, NV (2.1%). Additionally, depth of soil impacted SOC concentration and sequestration rate, decreasing both with increase in depth.

Differences in SOC concentration and pool in U.S. home lawns are attributed to differences in climatic and soil properties across ecoregions. The mean annual temperature (MAT) was negatively correlated with SOC concentration and pool, resulting in a 3.3% decline in SOC concentration for each 1°C increase in MAT. Furthermore, mean annual precipitation (MAP) indicated a nonlinear interaction on SOC concentration and pool. Increase in MAP in arid regions increased SOC concentrations, but its increase beyond the optimal MAP (60-70 cm yr⁻¹) decreased SOC concentrations. Soil nitrogen (N) concentrations were also highly correlated with SOC concentration and pool, with a 0.1% increase in soil N concentration resulting in a 0.99% increase in SOC concentration. Additionally, much like the interaction with MAP, soil bulk density (ρb) had a curvilinear correlation with SOC concentration and pool. At low ρb, increase in compaction resulted in increase in SOC concentration, however, as ρb increased above the optimal level (1.4-1.5 Mg m⁻³), decrease in SOC concentration was observed.

Rates of SOC sequestration ranged from 0.9 Mg C ha⁻¹ yr⁻¹ to 5.4 Mg C ha⁻¹ yr⁻¹, with a national average of 2.8 ± 0.3 Mg C ha⁻¹ yr⁻¹. As was observed for SOC concentrations, differences in rates of SOC sequestration are also attributed to differences in MAP, soil N concentrations, and ρb. However, SOC sequestration rate was also positively correlated with fine soil texture concentration and pH. On the basis of SOC sequestration and rate data, the potential C sink capacity of soils was determined. It ranged from 20.8 ± 1.0 Mg C ha⁻¹ in Portland, ME to 96.3 ± 6.0 Mg C ha⁻¹ in...
Minneapolis, MN, with an average across ecoregions of $45.8 \pm 3.5$ Mg C ha$^{-1}$.

Differences in potential C sink capacity are attributed to differences in MAT, MAP, soil N concentration, and $\rho_b$.

The hidden carbon costs (HCC) of home lawn establishment due to maintenance are also significant. Mean total emissions across sites is 0.25 Mg Ce ha$^{-1}$ yr$^{-1}$. Major HCC were due to mowing fuel combustion (0.19 Mg Ce ha$^{-1}$ yr$^{-1}$), and N fertilizer use (0.06 Mg Ce ha$^{-1}$ yr$^{-1}$). Taking into account total SOC sequestration potential and HCC due to maintenance emissions, SOC sequestered through home lawn establishment is negated by emissions by 170-198 years post lawn establishment. Mean potential SOC sink capacity for all home lawns in the State of Ohio and the U.S. is 17.8 and 496.3 Tg C, respectively. Additionally, the HCC due to maintenance under low management of these lawns is estimated at 82.6 and 2504.1 Gg Ce yr$^{-1}$. For soils held under high management regimes this estimation rises to 248.4 and 7551.4 Gg Ce yr$^{-1}$ for Ohio and the U.S.. This creates a C-positive system for 71-223 years for Ohio's home lawns and 66-199 years in the U.S..

In order to maximize the potential of home lawn turfgrasses to sequester SOC, when possible, turfgrasses should be established and managed where MAT is low, MAP is moderate, soil N concentrations are high, fine texture concentrations are maximized, pH is low, and $\rho_b$ is optimal. Additionally, HCC due to maintenance emissions should be minimized to increase the SOC sequestration longevity of home lawns and improve its benefits to GCC mitigation.
Dedication

Dedicated to my parents who have sacrificed greatly to see me succeed
Acknowledgements

I would like to thank my advisor, Dr. Rattan Lal, whose constant advice has helped further both my research and educational experience. Without his time and effort this project would not have been possible. I would also like to thank my committee members, Dr.’s Danneberger, Irwin, and Moore for their contribution to this dissertation and presentation.

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Additionally, special thanks goes to Basant Rimal, who aided greatly in the lab through analysis of soil samples in the C analyzer as well as Keely Bennett for her help with the statistical analyses.

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recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation
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Fields of Study

Major Field: Environmental Science
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<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>Mha</td>
<td>Million Hectares</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon Dioxide</td>
</tr>
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<tr>
<td>CH$_4$</td>
<td>Methane</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gasses</td>
</tr>
<tr>
<td>ACC</td>
<td>Accelerated Climate Change</td>
</tr>
<tr>
<td>SIC</td>
<td>Soil Inorganic Carbon</td>
</tr>
<tr>
<td>MAT</td>
<td>Mean Annual Temperature</td>
</tr>
<tr>
<td>MAP</td>
<td>Mean Annual Precipitation</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil Organic Carbon</td>
</tr>
<tr>
<td>GCC</td>
<td>Global Climate Change</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>MRT</td>
<td>Mean Residence Time</td>
</tr>
<tr>
<td>OM</td>
<td>Organic Matter</td>
</tr>
<tr>
<td>TSC</td>
<td>Total Soil Carbon</td>
</tr>
<tr>
<td>HDD</td>
<td>Heating Degree Days</td>
</tr>
<tr>
<td>CDD</td>
<td>Cooling Degree Days</td>
</tr>
<tr>
<td>$\rho_b$</td>
<td>Bulk Density</td>
</tr>
</tbody>
</table>
BMP = Best Management Practices

Ce = Carbon equivalent

P = Phosphorous

K = Potassium
Chapter 1: Introduction

As human population growth continues to proliferate, rapid urbanization and industrialization have become ever increasing environmental concerns. Global alterations of grasslands, forests, wetlands and a multitude of other native ecosystems are occurring to produce the food and shelter necessary to sustain an ever increasing population. Land use change, once considered a local issue, is now recognized for its global effects, as alterations are leading to numerous environmental impacts including atmospheric carbon (C) enrichment and the global climate change.

1.1 U.S. and Global Urbanization:

Over the decade ending in 2010, the U.S. population has increased by over 27 million (US Census, 2011a; Table 1.1). Due in part to this increase in population, U.S. metropolitan cities have also increased by an average of 66,000 people, with a total of more than 24 million Americans moving into urbanized areas. This shift represents an urban population increase of more than 10% in just 10 years (US Census, 2011b; Table 1.2). By the year 2000, such increases in urban population had led to a national urban land area of between 3.5 to 4.9%, or roughly 40.6 million hectares (Mha) nationally (Nowalk et al., 2001; Robbins and Birkenholtz, 2003). Accounting for a continued
population growth and anticipated personal income increase, this number may rise to 9.2% by 2025, a 79% increase in 15 years (Alig et al., 2004).

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>53,663,333</td>
<td>55,417,311</td>
<td>1,753,978</td>
<td>3.3</td>
</tr>
<tr>
<td>Midwest</td>
<td>64,491,889</td>
<td>66,972,887</td>
<td>2,480,998</td>
<td>3.8</td>
</tr>
<tr>
<td>South</td>
<td>100,559,291</td>
<td>114,404,435</td>
<td>13,845,144</td>
<td>13.8</td>
</tr>
<tr>
<td>West</td>
<td>63,451,331</td>
<td>72,256,183</td>
<td>8,804,852</td>
<td>13.9</td>
</tr>
<tr>
<td>United States</td>
<td>282,165,844</td>
<td>309,050,816</td>
<td>26,884,972</td>
<td>9.5</td>
</tr>
</tbody>
</table>

*Adapted from the U.S. Census Bureau (2011a) Table 1.1. Change in population for major regions over a 10 year period for the United States.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>857,903</td>
<td>128,255</td>
<td>17.6</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>5,475,213</td>
<td>1,227,192</td>
<td>28.9</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>88,854</td>
<td>7,247</td>
<td>8.9</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>6,447,615</td>
<td>1,286,078</td>
<td>24.9</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>2,552,195</td>
<td>372,852</td>
<td>17.1</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>276,368</td>
<td>883</td>
<td>0.3</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>5,867,489</td>
<td>1,152,072</td>
<td>24.4</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>1,902,834</td>
<td>527,096</td>
<td>38.3</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>3,269,814</td>
<td>301,002</td>
<td>10.1</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>2,082,421</td>
<td>437,863</td>
<td>26.6</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>4,364,094</td>
<td>1,112,206</td>
<td>34.2</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>516,826</td>
<td>29,261</td>
<td>6.0</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>3,407,848</td>
<td>363,951</td>
<td>12.0</td>
</tr>
<tr>
<td>Wichita, KS</td>
<td>612,683</td>
<td>41,510</td>
<td>7.3</td>
</tr>
</tbody>
</table>

| Mean All Metropolitan U.S. Cities | 703,156 | 66,345 | 10.0 |
| Total All Metropolitan U.S. Cities | 257,355,190 | 24,282,357 | 10.4 |

*Adapted from U.S. Census Bureau (2011b)
Table 1.2. Change in Population for major metropolitan areas sampled in this study.

Similarly, global urbanization trends have steadily increased over the past 50 years. As world population is likely to top 9 billion people by 2050, higher rates of urbanization are likely to occur over the next 40 years, especially in developing countries. UN estimations put global urbanization increasing to 69.9% by 2050, a significant increase from the 50.6% estimated in 2010. Such an increase is even higher in less developed regions because urbanization is expected to reach 67% by 2050, up by more than 20% from 45.3% in 2010 (UN, 2007; Table 1.3). This trend is especially significant as the industrialization of developing countries often leads to vastly accelerated...
combustion of fossil fuels and other C-intensive practices, which directly contribute to atmospheric carbon dioxide (CO₂) enrichment.

<table>
<thead>
<tr>
<th>Population (Billions)</th>
<th>% of Total</th>
<th>2010</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Developed Countries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.9</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>3.4</td>
<td>2.8</td>
<td>49.4</td>
</tr>
<tr>
<td>Urban</td>
<td>3.5</td>
<td>6.4</td>
<td>50.6</td>
</tr>
<tr>
<td>II. Less Developed Countries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.7</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>3.1</td>
<td>2.6</td>
<td>54.7</td>
</tr>
<tr>
<td>Urban</td>
<td>2.6</td>
<td>5.3</td>
<td>45.3</td>
</tr>
</tbody>
</table>

*Adapted from U.N. World Urbanization Prospectus (2007)
Table 1.3. Current and future world urbanization estimates.

1.2 Anthropogenic Carbon Emissions

It has been postulated that increases in population, affluence, and technology are the driving forces behind human environmental impact (I=PAT) (Ehrlich and Holdren, 1972). While population and affluence alone are estimated to expand the human impact on the environment by more than one-third in less than a decade (Dietz et al., 2007), others argue that the per capita level of consumption is solely responsible for the growth in greenhouse gas emissions (Satterthwaite, 2009). Regardless of the cause, land use change is at least partially responsible for a range of environmental concerns, including the release of significant concentrations of climate altering C emissions. The 150 year
period between 1850 and 2000 has witnessed estimated direct C emissions due solely to land use changes of 136 ± 55 Pg C (Houghton, 1995; Houghton, 1999). Since 1850, it has been estimated that 35% of all the anthropogenic CO$_2$ emissions have been a direct result of land use changes (Houghton and Hackler, 1994).

There are numerous types of land use changes, each contributing significantly to a range of environmental concerns. One such type of change is the degradation of forest ecosystems which have been estimated to produce especially large C fluxes (Brown et al., 1994; Flint and Richards, 1991; Flint and Richards, 1994; Houghton, 1991; Houghton and Hackler, 1994). The direct clearing and subsequent cultivation of forest soils can lead to the emission of between 25-30% of their C pools (Detwiler, 1986; Schlesinger, 1986; Davidson and Ackerman, 1993).

Forest degradation in the tropics may be particularly important as large areas of biomass are cleared on an increasingly regular basis to make way for cultivation and grazing. Since the 1970's, degradation of tropical rainforest systems with their high diversity and biomass increased by over 90% into the late 1980's (Myers, 1991). This is of increasing concern as the intense amount of clearing in tropical forest regions have created C losses over ten times those of forest systems in temperate climates (Houghton and Skole, 1990a). It is estimated that the clearing of tropical forest systems may release large amounts of CO$_2$, with some clearing being done for the construction of urban centers.

Urbanization is also encroaching upon wetlands. Indeed, wetland drainage and destruction is another area of land use change that is cause of major concern. While these are particularly sensitive areas of high biodiversity and wildlife habitat, wetlands also
play a vital role in the global C cycle storing up to as much as 0.29 Mg C ha\(^{-1}\) yr\(^{-1}\) (Lal et al., 1995). It has been estimated that global mangrove swamps and salt marshes alone are responsible for storage of at least 44.6 Tg C yr\(^{-1}\) (Chmura et al., 2003). With such large C sequestration potential, land use alterations of such ecosystems may lead to massive C emissions and increased risks of climate change. For instance, the drainage of peatlands for agricultural cultivation contributed between 0.063 and 0.085 Pg of C yr\(^{-1}\) with an additional 0.032 to 0.039 Pg of C yr\(^{-1}\) due to peat combustion by the 1980's (Lal et al., 1995). Zhang et al. (2008) reported that disturbance of wetland soils leads to an almost immediate 400% increase in soil CO\(_2\) emissions.

Land use change of any kind can alter the C dynamics of a system. Soil perturbation can deplete soil organic matter (SOM) pools and directly release soil organic carbon (SOC) to the atmosphere as CO\(_2\) (Schlesinger, 2000). This is especially true for agricultural ecosystems, which are often the primary cause for initial land use alterations. Cultivation of land for crop production leads to a serious decline in the SOM pools (Post and Mann, 1990). More specifically, there exists a direct relationship between the decrease in SOM over time with the increase in duration of cultivation (Brams, 1971; Jenkins and Ayanuba, 1977; Lal, 1979). Estimates of SOM lost are as high as 20-40% upon conversion of natural ecosystems (Schlesinger, 1986; Mann, 1986; Detwiler, 1986), while prairie converted agricultural soils may lose up to 43% of their antecedent SOC pools (Potter et al., 1999). Regardless, as of 1980, conversion of land for agricultural use and intensive farming has emitted between 90 and 120 Pg of C since 1850 (Houghton and Skole, 1990b).
The magnitude of SOC loss attributed to cultivation and urbanization often hinge upon land use and agricultural practices under site-specific conditions. For instance, plowing increases SOC loss as CO$_2$ (Reicosky, 2002; Reicosky et al., 1999). In addition, farming practices have high hidden carbon costs (HCC). The use of a moldboard plow can use up to 50 L of diesel fuel per hectare (Koller, 1996). Additionally, the use of fertilizers and manures, vital to the farming industry, lead to large emissions of both CO$_2$ and methane (CH$_4$) (Minami et al., 1994). Since the mid 1970's, there has been over a 700% increase in the use fertilizers (Matson et al., 1997; Tilman et al., 2001). In addition to fertilizer production and use, the need for water to produce crops in arid climates has increased the need for supplemental irrigation. With the increase in fertilizer use, there has also been over a 70% increase in irrigated crop land area (Rosegrant et al., 2002; Gleick, 2003).

While agricultural practices, deforestation, and wetland disturbance are all significant contributors to global anthropogenic C emissions, one of the most significant contributors is through the combustion of fossil fuels. As population growth and urbanization continue to increase, so too will fossil fuel combustion, not only to produce crops, but fuel transportation, heat homes, and manufacture a large quantity of the products utilized in daily life. From the dawn of the industrial revolution through 1998, 270 ± 30 Pg of C were emitted through fossil fuel combustion and cement production alone (Marland et al., 1999), with an estimated 176 ± 10 Pg being directly released and absorbed by the atmosphere (Ethridge et al., 1996; Keeling and Whorf, 1999). With an increasing reliance on fossil fuels, these emissions will only continue to increase with the increase in need to house and feed an ever growing population.
1.3 Carbon Emissions and Climate Change

Anthropogenic C emissions are responsible for the release of significant amounts of greenhouse gasses (GHG), most commonly in the forms of CO₂ and CH₄. The release of significant amounts of these gasses are contributing to accelerated climate change (ACC) (IPCC, 2007). The effects of ACC can be directly observed as overall global temperatures have increased by 0.74°C (IPCC, 2007) at a rate of 0.16°C per decade since the late 19th century (NOAA, 2008). This global temperature rise is attributed in part to a 38% increase in CO₂ concentration and a 157% increase in CH₄ concentration over the same time period, leading to a substantial enrichment of the global atmospheric C pool (WMO, 2009; Lal 2004a). Atmospheric concentrations of GHG continue to rise as increased population and technological advancement lead to greater rates of land use change and fossil fuel combustion. The current atmospheric concentration of CO₂ has reached 390ppm, up over 100ppm since the coming of the industrial revolution. It is estimated that a 3% increase in CO₂ emissions within the current decade would lead to atmospheric CO₂ concentrations of over 450ppm by 2025. This in turn would translate into a global temperature increase of between 1 and 1.5°C above the pre industrial levels (Raupach et al., 2007). Further estimates by the IPCC (2007) show low C emission scenarios leading to average global temperature increases of between 1.1 and 2.9°C and high C emissions estimates leading to temperature increases as high as 2.4 to 6.4°C by the turn of the century.

Even slight alterations in mean temperature can have significant effects on the global environment. SOM pools respond negatively to even small increases in air temperature. Soils located in warmer climates tend to have much lower SOC pools, both
in concentration and quality (Sachs and Luff, 2002; Karhu et al., 2010). This has been observed directly as SOM pools in soils held under a mean temperature of 32°C are 9 times higher than those held in soils whose temperatures remain at 70°C (Sachs and Luff, 2002). This trend could have dramatic effects in a warming world as a 3°C change in global temperature could deplete as much as 15% of the SOC pools in the arid zone, 20% in the sub humid zone, and 28% in the humid zone (Bottner et al., 1995). Not only would this prove detrimental to the soil, which would lose productivity and fertility, but would also lead to increases in the atmospheric CO₂ concentration.

Additionally, the SOC sequestration potential of soils can be affected through the warming effects on photosynthesis and decomposition, creating soils that are able to hold less C (Sjogersten and Wookey, 2009). The rising global temperatures can increase soil respiration, providing a positive feedback that will contribute to increased future warming (Wiant, 1967; Schleser, 1982; Schlentner and Van Cleve, 1985; Raich and Schlesinger, 1992; Peterjohn et al., 1993).

Increased warming also creates large losses of C through substantial shifts in diverse global vegetation zones (Bachelet et al., 2001). A 1°C global temperature increase can shift vegetation zones poleward by an estimated 200 km (Ozenda and Borel, 1990; Beckage et al., 2008; Metzger et al., 2008). Finally, global temperature increases can alter global precipitation. A warming climate may increase surface precipitation in the northern hemisphere by as much as 1% per decade while decreasing the surface precipitation in the southern hemisphere by 0.3% per decade (Lal, 2004a).

Anthropogenic C emissions can drastically alter the global environment. Additionally, while leading to the direct heating of the Earth, they other impacts include the loss of
SOM, shifts in vegetation zones, altered global precipitation patterns, and a range of additional adverse environmental consequences.

1.4 Global Carbon Pool

There are 5 principal global C pools. The Oceanic pool, which contains the most C consists of a surface layer holding 900 Pg, a deep and intermediate layer holding 37,100 Pg, a biotic marine component holding 3 Pg, and a surface sediment component comprising 150 Pg, for a total of 38,153 Pg of C within the Oceanic pool. There is a net positive flux into the ocean of around 2.3 Pg C yr⁻¹, as approximately 90 Pg C yr⁻¹ are emitted from the oceans with 92.3 Pg C yr⁻¹ being absorbed from the atmosphere. An additional 0.7 Pg C yr⁻¹ are absorbed into the oceanic pool annually through sediment deposit and weathering (Lal, 2008).

The geologic or fossil fuel pool is the second most prevalent, consisting of C held as coal (3510 Pg C), oil (230 Pg C), gas (140 Pg C), and other (250 Pg C) for a C pool of 4130 Pg C. Of this 4130 Pg, 7.5 Pg C yr⁻¹ are emitted from the geologic pool directly into the atmosphere through fossil fuel combustion (Lal, 2008).

The pedologic or soil pool is greater than both the atmospheric and biotic pools combined, holding an estimated 2500 Pg of C, with 1550 Pg C as SOC and 950Pg C as soil inorganic carbon (SIC) (Lal, 2008). There is some disagreement as to the specific amount of C held in the pedologic pool with some research estimating the SOC pool ranging between 1400 and 1500 Pg C in its SOM (Schlesinger, 1977; Post et al., 1982; Eswaren et al., 1993) while others estimate the SOC pool to range between 1220 and 1550 Pg C to 1 m depth and between 2376 and 2450 Pg C to 2 m depth (Eswaren et al.,
Additional research estimates the total SIC pedologic pool between 695 and 748 Pg C to a 1 m depth (Batjes, 1998). In all cases, total soil C decreases with increase in depth (Golubiewski, 2006). Fluxes of 60 Pg C yr\(^{-1}\) out of the pedologic pool due to soil respiration are replaced by addition of 60 Pg C yr\(^{-1}\) from the biotic pool. However, soil erosion is responsible for the loss of around 1 Pg C yr\(^{-1}\) to the atmosphere (Lal, 2008).

The atmospheric pool is estimated to hold 780 Pg C. Atmospheric C enrichment of 3.5 Pg C yr\(^{-1}\) is due to fossil fuel combustion, soil erosion and deforestation. Conversion of 120 Pg C yr\(^{-1}\) to biomass through photosynthesis is negated by soil and plant respiration (Lal, 2008).

The biotic C pool consists of 560 Pg C with conversion of 60 Pg C yr\(^{-1}\) from belowground biomass mineralization being replaced by photosynthetic activity (Lal, 2008; Figure 1.1). All of the values listed are estimates, however, they provide vital information as to the importance of a balanced C budget. Direct analysis of pedologic pools indicate emissions from soils into the atmosphere (Houghton et al., 1983; Houghton et al., 1985; Houghton et al., 1987; Detwiler and Hall, 1988; Houghton and Skole, 1990a; Hall and Uhlig, 1991; Houghton, 1991; Flint and Richards, 1994; Post et al., 2004). Such emissions from the SOC pool could overwhelm the atmospheric pool with CO\(_2\). Between 1850 and 1980 the worlds soils lost between 90 and 120 Pg of C due to a number of anthropogenic activities such as deforestation, cultivation, and general land use change (Houghton and Skole, 1990a). If this intensity of pedologic C loss continues, major environmental consequences may result from emission into the atmospheric pool.
(From Lal, 2008)
Figure 1.1. The global carbon pool with 5 principal pools and fluxes among them.

1.5 Soil Organic Matter

The SOM serves numerous positive environmental functions within an ecosystem.

High concentrations of SOM can be an invaluable resource for not only the direct health of the soil but also for the health of the surrounding environment. Characteristics such as its high water absorption capacity can lead to increased plant available water while its elevated infiltration capacity allows for proper soil moisture while limiting the losses from surface runoff. Additionally, high concentrations of SOM can decrease erosional losses by promoting soil aggregation to improve overall soil tilth and by strengthening the aggregates making them less detachable. By limiting soil erosion, the surrounding areas are protected, and decreased soil erosion means a reduction in sedimentation of waterways and reservoirs.
The SOM has a number of other beneficial environmental functions, including functioning as substrate for soil biota, enhancing ion exchange capacity, buffering against pH changes, and moderating soil temperature through its effects on albedo. Furthermore, it can mitigate many of the negative effects of cultivation by filtering pollutants, including many harmful agricultural chemicals, and directly buffering GHG emissions from the atmosphere through its soil C sequestration capacity (Lal, 2004a).

With numerous benefits, SOM plays a vital role in the health of an ecosystem. However, as high concentrations of SOM produce a number of beneficial functions, depletion of the SOM pool through intensive farming, deforestation, and land use change can reverse the benefits reaped through years of SOM enhancement.

1.6 Soil Carbon Sequestration Potential

With the continued population growth and the subsequent urbanization of natural landscapes, SOC pools are being depleted at an alarming rate. While this trend is leading to a range of environmental concerns, improved soil management may provide the means to resequester much of the C lost through cultivation and land use change (Kauppi et al., 2001).

Annually, photosynthesis is responsible for the uptake of 120 Pg C by the biota. However, due to respiration, the mean residence time (MRT) of C in the biotic pool is just 5 years. Additionally, soil and plant respiration together emit 120 Pg C into the atmosphere. Thus, if a proportion of this C could be sequestered by soils instead of released, it could lengthen the MRT of C in the biotic pool and prove an effective tool in slowing the rate of atmospheric CO₂ enrichment (Lal, 2004b). This goal of atmospheric
C sequestration can be accomplished through a variety of strategies. Restoration of drained wetlands can increase SOC pools and sequester significant amounts of C over time (Gleason and Euliss, 1998). Similarly, reforestation of deforested regions can lead to a resequestration of much of the C lost to the atmosphere (Lal, 2001; Kimble et al., 2003). However, one of the most promising methods of enhancing the SOC pool is through the restoration of abandoned and degraded croplands. Croplands have lost as much as 60 Mg C ha\(^{-1}\). However, if managed properly, the restoration of cultivated soils can resequester much of this lost C over a period of 50 years (Lal et al., 2000). Such a strategy could be effective in counteracting the massive annual C emissions due to fossil fuel combustion.

While restoration of degraded cultivated soils can sequester C at rates of 0.031 Mg C ha\(^{-1}\) yr\(^{-1}\) (Burke et al., 1995), conversion of these soils to grasslands may also increase the sink capacity. The growth of perennial grasses on previously cultivated land can sequester C at 0.33 Mg C ha\(^{-1}\) yr\(^{-1}\) (Post and Kwon, 2000), and as much as 1.1 Mg C ha\(^{-1}\) yr\(^{-1}\) with improved management (Gebhart et al., 1994; Mensah et al., 2003).

While establishment of grasslands enhances SOC pool in degraded cultivated soils, managed turfgrass establishment may also sequester C over time. Conversion to turfgrass systems can improve fertility as turf soils receive chemical fertilizers (Conant et al., 2001), which in turn can enhance the gross SOC pools. Turfgrass proliferation in the form of golf course establishment can sequester C at rates of 0.90 Mg C ha\(^{-1}\) yr\(^{-1}\) when established on previous grassland sites, and as much as 3.58 Mg C ha\(^{-1}\) yr\(^{-1}\) when established on cultivated soils (Qian and Follett, 2002; Selhorst and Lal, 2011). While the sequestration benefits of golf course establishment are significant, the HCCs due to
turf establishment are also large. The C emitted through fossil fuel combustion for fertilizer use, pesticide application, and a range of other maintenance practices can lessen if not completely negate the benefits of the enhanced SOC pool (Witteven and Bavier, 2005).

While maintenance emissions in golf course turfgrasses may negate many of the potential C pool enhancement benefits, home lawns may provide a more effective mean of sequestering C. As increased population and urbanization lead to the ever increasing number of single family homes and subsequent manicured lawns, these turfs may sequester atmospheric CO2. If they sequester C at rates similar to golf courses, their overall benefits may exceed those of golf turf systems as home lawn inputs are far lower than those for highly managed golf course systems.

1.7 Climatic and Soil Effects on Soil Carbon Pool:

While home lawn turfgrasses sequester large amounts of the historic SOC loss, numerous climatic and soil factors are important to the process. Mean annual temperature (MAT) for instance is correlated with the SOC pool (Jenny, 1941; Post et al., 1982). However, the available literature is controversial (Giardina and Ryan, 2000; Knorr et al., 2005). Similarly, mean annual precipitation (MAP) also has a significant influence on SOC pools. Generally, increased MAP leads to increases in SOC concentration (Jenny, 1941; Post et al., 1982; Amelung, et al., 1997). However, similar to MAT, MAP can also be negatively correlated with SOC concentration (Marton, 2008), probably due to the interaction between MAP and numerous SOC pool altering soil properties.
Soil properties such as texture, acidity, and bulk density ($\rho_b$) vary across regions. Variations in these properties may increase or decrease a soil's capacity to sequester C. Soil clay content, for instance, can affect SOC storage (Tron et al., 1997; Burke et al., 1989). However, SOC concentration in some grasslands is not correlated with the clay content (Percival et al., 2000). Soil $\rho_b$ may also significantly affect SOC pools. Increases in $\rho_b$ may increase the soil mass for sequestration. However, beyond a threshold, compaction can limit the SOC sequestration potential (Brevik et al., 2002). Additionally, soil acidity may also alter the SOC pools. Through the alteration of microbial properties, differences in pH may lead to variations in SOC sequestration over diverse regions (Walse et al., 1998; Spiegelberger et al., 2006).

Climatic factors and soil properties can alter SOC pools. However, it is unlikely that these variables work independently of one another. The interaction between variables is likely to affect the SOC sequestration potential.

This study is designed to address many of the knowledge gaps spawning from the literature review. Investigation into the interaction between climate and home lawn SOC sequestration can provide vital information into optimal sites for climate mitigation potential. Additionally, this research will provide data over a large spatial scale, whereas previous studies have either focused on greenhouse experiments or have been conducted at regional scales. The following work will also serve to determine key soil properties involved in home lawn SOC sequestration. Such data could identify both optimal soil properties and management techniques for maximizing the SOC sequestration potential of U.S. home lawns.
1.8 Objectives:

The specific objectives of this research are as follows:

i. Determine the capacity of U.S. home lawn turfgrass systems to sequester SOC over time.

ii. Ascertain the relationship between key soil properties and climatic variables and assess the potential C sink capacity of U.S. home lawns.

iii. Determine the potential of Ohio and U.S. home lawns to off-set C emissions in lieu of estimated HCC.

iv. Identify management recommendations to increase the C sequestration potential of U.S. home lawn turfgrasses.

v. Identify research gaps and provide suggestions for future exploration into turfgrass systems.

1.9 Hypotheses:

The hypotheses tested in this study are as follows:

i. U.S home lawns have a potential to sequester SOC over time at varying rates across a large spatial scale.

ii. The SOC pool, rate of sequestration, and potential C sink capacity in U.S. home lawn turfgrasses increases with increase in clay content and soil acidity.

iii. In U.S. home lawn turfgrasses, the SOC pool, rate of sequestration, and potential C sink capacity increase with decrease in temperature and increase in precipitation.
v. The overall capacity of U.S. home lawn turfgrasses to sequester C and mitigate atmospheric CO₂ enrichment can be significant for approximately 30 years, after which soils become C saturated and operate as a source due to the HCC of lawn maintenance.

Chapter 2 addresses the first objective. It describes the capacity of U.S. home lawn turfgrasses to sequester SOC over time and will help determine the overall rate of SOC sequestration following turfgrass establishment.

Chapter 3 addresses the second objective by discussing the effects of climate on U.S. home lawn SOC sequestration. It assesses the effects of temperature and precipitation as well as numerous soil properties on the SOC pool. Additionally, it addresses the effects of numerous soil properties on the SOC pool to help explain variations in SOC pools across spatial differences.

Chapter 4 addresses objective three by discussing the net SOC sequestration potential of both Ohio and U.S. home lawns. The management related emissions are also discussed in the context of lawn climate change mitigation potential.

Chapter 5 addresses objectives four and five by summarizing the effect of home lawn turfgrass development and a synopsis of current research gaps and possible future studies.

References


Chapter 2: Soil Organic Carbon Sequestration Following Home Lawn Development

Abstract

Turfgrass systems sequester carbon (C) when established on degraded soils. Analyses of soil from turfgrass under diverse ecoregions indicate that home lawns throughout the United States can sequester a significant amount of soil organic carbon (SOC) over time. Rates of SOC sequestration ranged between 0.01% yr^{-1} and 0.70% yr^{-1} depending on location and depth, sequestering SOC by 2-3%. Exceptionally high SOC concentrations, were observed in Minneapolis, MN (5.6%), Wooster, OH (3.4%), Denver, CO (3.2%), and Duluth, MN (3.1%). Conversely, notably low SOC concentrations were measured in Atlanta, GA (1.5%). Soil inorganic carbon (SIC) concentrations were high in numerous hot, dry climates, especially those of Dallas, TX (2.2%), and Las Vegas, NV (2.1%). Soils initially sequester SOC to 15 cm depth for ~18 years after which time SOC concentrations stabilize for ~40-60 years before once again increasing. Time for initial sequestration ranged from 13 to 31 years at 0-2.5 cm depth and from 8-43 years at 2.5-15 cm depth. Depth of soil also significantly affected the SOC, with concentration decreasing with increase in soil depth.

Key Words: Turfgrass, Home Lawns, Soil Organic Carbon, Carbon Sequestration, Carbon Sequestration Rate

2.1 Introduction

As increases in human population and urbanization lead to expansive land use change and cultivation, soil organic carbon (SOC) pools are being depleted globally. While this leads to numerous environmental concerns, a strategy of reversing this trend
may allow soils to sequester large amounts of carbon (C), thus potentially offsetting a fraction of the global fossil fuel emissions (Kauppi et al., 2001).

Globally each year 120 Pg C are photosynthesized from the atmosphere terrestrially, however, most is returned to the atmosphere through soil and root respiration. If just one tenth of this 120 Pg C were retained in the soil and biosphere, it would be enough to offset annual global anthropogenic fossil fuel emissions (Lal, 2004). This strategy could be a long-term climate change mitigation solution, as the passive SOC pool has an estimated turnover time of over 2200 years (Woomer et al., 1994; Parten et al., 1987). Additionally, SOC enhancement may also mitigate another impending problem associated with global population increase, the food insecurity. As well as its capacity to offset fossil fuel emissions, it is estimated that a 1 ton increase in the SOC pool of a degraded cropland soil may increase agronomic yields by as much as 0.02-0.04 Mg ha\(^{-1}\) for wheat (\textit{Triticum aestivum}) and 0.3-0.4 Mg ha\(^{-1}\) for corn (\textit{Zea mays}) (Lal, 2006). With global increase in population by over 3 billion expected by the end of the 21st century, increase in agriculture efficiency may provide immense benefits and reduce the land area required to feed the growing population.

There are a number of strategies to achieve this goal of SOC pool enhancement. One such strategy is the restoration of wetland ecosystems. Among other environmental benefits, wetlands increase SOC pools by reducing decomposition rates and deposition/burial of eroded topsoils (Gleason and Euliss, 1998). Similarly, restoration and replanting of forest ecosystems has a potential of SOC sequestration, especially with reforestation of degraded agricultural sites (Lal, 2001; Kimble et al., 2003). Afforestation has the potential to sequester as much as 1.0 Mg ha\(^{-1}\) yr\(^{-1}\) (Johnston et al., 1996). Both of
these methods are important to the health of the environment as increased urbanization is resulting in the alteration of these ecosystems and the attendant release of SOC pool.

While aorestation and wetland restoration may be a viable strategy of SOC pool enhancement, restoration and management of degraded and depleted croplands may have the greatest potential to sequester SOC over time. Much of the worlds croplands may have lost as much as 60 Mg C ha\(^{-1}\), however, the depleted soils may re-sequester C for as much as 50 years (Lal et al., 2000). Such a capacity is equivalent to a C sequestration potential of 0.43 to 0.57 Pg C yr\(^{-1}\) (Lal and Bruce, 1999). This is a significant amount of C that could have substantial effects on the global SOC pool.

Possibly the largest potential to sequester C and increase the SOC pools of depleted agricultural soils is to revert back to its antecedent land use. Restoration of agricultural soils can sequester as much as 0.031 Mg C ha\(^{-1}\) yr\(^{-1}\) to 10 cm depth (Burke et al., 1995). When complete reversion to a prior land use is not possible, land improvement has the capacity to sequester much of the historic SOC loss. For instance, improvement of grazing lands and pasture, achievable through a variety of techniques, can sequester 0.11 to 3.04 Mg C ha\(^{-1}\) yr\(^{-1}\) (Conant et al., 2001). However, this strategy for SOC pool enhancement will prove limited, as cultivation will remain necessary to feed a growing population.

Continued population growth and the subsequent urbanization of land has resulted in the conversion of wetlands, forests, and other native lands for the expansion of cities and to cropland cultivation. These land use changes lead to a depletion of SOC pools, and significantly contribute to global atmospheric carbon dioxide (CO\(_2\)) enrichment. While wetland restoration and aorestation may not be feasible in some areas, the
introduction of grasses on degraded and surplus lands may improve the SOC pool and increase the biomass productivity of soils. Furthermore, conversion to a retroactive land use and pasture improvement can be an effective method of resequestering much of the SOC previous lost, because conversion of cultivated soils to grasslands has the potential to enhance the SOC pool. Introduction of perennial grasses in abandoned agricultural fields can sequester SOC at rates of 0.33 Mg C ha\(^{-1}\) yr\(^{-1}\) (Post and Kwon, 2000) and 1.1 Mg C ha\(^{-1}\) yr\(^{-1}\) with improved management (Gebhart et al., 1994; Mensah et al., 2003). Upon conversion from agricultural lands, SOC sequestration in grasslands can occur for up to 158 years (Potter et al., 1999).

While the conversion of disturbed lands to grassland settings can sequester SOC over time, introduction of managed turfgrasses may have a greater capacity to enhance the SOC pool. As managed turfgrasses generally receive regular inputs of fertilizers, pest management, and irrigation, their increased soil management can increase their potential C sink capacity. Huh et al. (2008) observed that conversion of grasslands to golf course turfgrass systems can sequester SOC at rates of as much as 0.69 Mg C ha\(^{-1}\) yr\(^{-1}\). If sequestration rates of this magnitude are possible upon conversion of grassland soils, conversion of disturbed wetlands, cleared forests, and SOC depleted cultivated soils may attain higher SOC pool enhancement.

The SOC advantages of turfgrasses may prove especially beneficial as increased urbanization is resulting in the accelerated construction of single family homes accompanied by managed lawns. If these home lawns SOC at rates similar to those reported for other turfgrass systems, they may provide an effective strategy for enhancing the SOC pool in urbanized regions. Additionally, construction of home lawns on
previously disturbed soils may increase the C sink capacity of the soils and enhance their capacity to offset global CO₂ emissions.

The following chapter is aimed at determining the capacity of U.S. home lawns to sequester SOC over time. It is hypothesized that home lawn turfgrasses nationwide have the potential to sequester SOC at a range of rates. If this hypothesis is proven and land use and management practices are properly adopted, home lawn turfgrasses in the U.S. may slow the rate of atmospheric CO₂ enrichment and partially mitigate the effects of global climate change (GCC).

### 2.2 Materials and Methods

**Site Descriptions:**

Soil samples were obtained from home lawns in 16 sites located throughout the United States. The country was divided into 8 turfgrass regions based on climate and types of grass species grown in each region (Figure 2.1). Within each turfgrass climatic region, two sites were chosen for soil analysis. Sites within each region were chosen where turfgrass establishment was abundant and home lawns were assumed to receive management typical of other lawns in the region (Table 2.1). Sites were also chosen to allow for sampling of soils located in regions with a wide range of mean annual temperature (MAT) and mean annual precipitation (MAP) ranges (Table 2.2). Within each city, home lawns chosen for sampling were selected based on the number of years since turfgrass development. Additionally, the median home price in each city was obtained (Table 2.1) and all lawns sampled were on properties valued at ±$50,000 within
this median price. This was done to limit any residual effects of income on home lawn maintenance. Between 7 and 11 lawns were sampled with each differing in age by approximately 10 years and representing an age chronosequence range of up to 100 years. It is assumed that all lawns are the same age as the homes that they accompany. Additionally, one native land use site located within all other sampling sites was also chosen for sampling of year 0. Native land use sites represented most probable land use prior to lawn establishment (i.e. grasslands in Wichita, KS, forests in Seattle, WA). Cultivated soils were never used as a native land use site.

Figure 2.1. Map of turfgrass climatic regions and sampling sites indicated by a red star.
<table>
<thead>
<tr>
<th>Metropolitan Area</th>
<th>Population&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Mean Home Value (Dollars)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>857,903</td>
<td>35º05'04&quot;N</td>
<td>106º39'04&quot;W</td>
<td>189,700</td>
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<td>Atlanta, GA</td>
<td>5,475,213</td>
<td>33º44'56&quot;N</td>
<td>84º23'16&quot;W</td>
<td>257,200</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>88,854</td>
<td>41º08'23&quot;N</td>
<td>104º49'12&quot;W</td>
<td>168,100</td>
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<td>Dallas, TX</td>
<td>6,447,615</td>
<td>32º48'10&quot;N</td>
<td>96º46'11&quot;W</td>
<td>153,600</td>
</tr>
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<td>Denver, CO</td>
<td>2,552,195</td>
<td>39º44'20&quot;N</td>
<td>104º59'04&quot;W</td>
<td>244,600</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>276,368</td>
<td>46º47'12&quot;N</td>
<td>92º06'01&quot;W</td>
<td>151,200</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>5,867,489</td>
<td>29º45'46&quot;N</td>
<td>95º22'59&quot;W</td>
<td>128,000</td>
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<tr>
<td>Las Vegas, NV</td>
<td>1,902,834</td>
<td>36º06'52&quot;N</td>
<td>115º10'22&quot;W</td>
<td>197,000</td>
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<td>Minneapolis, MN</td>
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<td>44º58'47&quot;N</td>
<td>93º15'49&quot;W</td>
<td>220,900</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>2,082,421</td>
<td>28º32'18&quot;N</td>
<td>81º22'45&quot;W</td>
<td>296,369</td>
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<tr>
<td>Phoenix, AZ</td>
<td>4,364,094</td>
<td>33º26'54&quot;N</td>
<td>112º04'26&quot;W</td>
<td>182,300</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>516,826</td>
<td>43º39'41&quot;N</td>
<td>70º15'19&quot;W</td>
<td>257,200</td>
</tr>
<tr>
<td>San Francisco, CA</td>
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<td>122º25'09&quot;W</td>
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<tr>
<td>Seattle, WA</td>
<td>3,407,848</td>
<td>47º36'22&quot;N</td>
<td>122º19'55&quot;W</td>
<td>452,000</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>612,683</td>
<td>37º41'32&quot;N</td>
<td>97º20'15&quot;W</td>
<td>115,800</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>857,903</td>
<td>40º48'18&quot;N</td>
<td>81º56'06&quot;W</td>
<td>122,900</td>
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</tbody>
</table>

<sup>a</sup>Adapted from the US Census Bureau (2011)

<sup>b</sup>Data obtained from city-data.com

Table 2.1. List of all sites sampled in this study with location and metropolitan population.
<table>
<thead>
<tr>
<th>Metropolitan Area</th>
<th>Grass Species</th>
<th>Soil Order&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Mean Annual Temperature&lt;sup&gt;b&lt;/sup&gt; (ºC)</th>
<th>Mean Annual Precipitation&lt;sup&gt;b&lt;/sup&gt; (cm yr&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>Bermuda (Cynodon dactylon)</td>
<td>Aridisols</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>Zoysia (Zoysia matrella)</td>
<td>Entisols</td>
<td>17</td>
<td>140</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>KY Blue (Poa pratensis)</td>
<td>Mollisols</td>
<td>7</td>
<td>39</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>Zoysia (Zoysia matrella)</td>
<td>Vertisols</td>
<td>19</td>
<td>88</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>KY Blue (Poa pratensis)</td>
<td>Mollisols</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>KY Blue (Poa pratensis)</td>
<td>Inceptisols</td>
<td>4</td>
<td>79</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>St Augustine (Stenotaphrum secundatum)</td>
<td>Vertisols</td>
<td>20</td>
<td>122</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>Bermuda (Cynodon dactylon)</td>
<td>Entisols</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>KY Blue (Poa pratensis)</td>
<td>Mollisols</td>
<td>7</td>
<td>75</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>St Augustine (Stenotaphrum secundatum)</td>
<td>Entisols</td>
<td>23</td>
<td>123</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>Bermuda (Cynodon dactylon)</td>
<td>Aridisols</td>
<td>23</td>
<td>21</td>
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<tr>
<td>Portland, ME</td>
<td>KY Blue (Poa pratensis)</td>
<td>Inceptisols</td>
<td>8</td>
<td>116</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>Bent (Agrostis palustris)</td>
<td>Inceptisols</td>
<td>14</td>
<td>51</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>Bent (Agrostis palustris)</td>
<td>Inceptisols</td>
<td>11</td>
<td>94</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>Buffalo (Buchloe dactyloids)</td>
<td>Mollisols</td>
<td>14</td>
<td>77</td>
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<tr>
<td>Wooster, OH</td>
<td>KY Blue (Poa pratensis)</td>
<td>Alfisols</td>
<td>10</td>
<td>97</td>
</tr>
</tbody>
</table>

<sup>a</sup>Data from NRCS, 2011
<sup>b</sup>Data from NOAA, 2008

Table 2.2. List of all sites sampled in this study with climatic region, mean annual temperature, and mean annual precipitation data.

**Experimental Design:**

Three soil samples were obtained from each lawn and native sampling site within each city. Each yard was separated into three sections to account for variations in slope,
shade, etc. One sample was taken from each of the three subdivided sections. All samples were taken at least three meters from the actual home and from any trees located within the yard. These three samples would be utilized for the determination of total C concentration, pH, and the concentration of soil inorganic matter (SIC) present to depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm.

**Soil Sampling and Analyses:**

All soil samples were obtained between October 1, 2009 and October 1, 2010. At each home lawn site, three core samples were obtained to a depth of 15 cm, using 5.4 cm (2 inch) diameter PVC pipe. Pipes were driven into the ground using a rubber mallet to a depth of 15 cm and extracted, leaving the soil core intact.

The three cores were removed from the PVC pipe by forcing through one end, allowing for removal from the pipe while keeping the soil profile intact. The cores were then divided into four sections by depth as follows; 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm. Each layer was then air dried, gently ground using a wooden roller, sieved through a 2 mm sieve and all remaining litter and root material were removed and weighed. Samples were then further ground, sieved through a 0.125 mm sieve, placed in 10 ml vials containing two stirring magnets and ball milled for a period of 24 hours.

A subsample of the finely ground soil was then utilized for C concentration analysis for each site for four separate depths using the dry combustion method with an NC 2100 soil analyzer (ThermoQuest CE Instruments, Milan, Italy). The data were expressed on % dry soils basis (g/100g).
A second subsample of the ground soil was then mixed with deionized water in a 1:1 solution and the pH determined using a soil pH meter (USDA, 1996). For soil samples with a pH<7.5, total soil C was assumed to be SOC (Bohn et al., 1985).

For soils with a pH>7.5, a third subsample of the ground soil was treated with hydrochloric acid and the total SIC concentration in each sample was determined by the method of Kennedy et al. (2005). The total SIC was subtracted from the total C concentration determined through the dry combustion analysis to determine the total SOC concentration in each sample.

**Statistical Analysis:**

For each site, the SOC concentration was plotted against the number of years since turfgrass establishment for all sites at each depth. Using SAS Statistical procedures (SAS Institute Inc., 1994) a nonlinear regression analysis was performed on each plot to determine the amount of SOC sequestered per year per site per depth. Additionally, maximum SOC sequestration rate was determined from the slope of the nonlinear regression analysis. Minitab 14.1 was also utilized to run one-way ANOVAs with Tukey's post tests to determine if there were statistically significant differences between the SOC concentrations of soils located in different locations and at various depths.

**2.3 Results and Discussion**

**Soil Organic Carbon Sequestration:**

**Temporal Changes in Soil Organic Carbon Sequestration:**
Nonlinear regression analysis for each sample site indicated SOC sequestration following turfgrass establishment. However, soils located in diverse regions sequestered SOC at varying rates and to various degrees. Soils located in Minneapolis, MN indicated the highest SOC sequestration over time. Figure 2.2 shows the percent SOC sequestration following home lawn turfgrass establishment over an 83 year period at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm for home lawns located within Minneapolis, MN. The nonlinear regression analysis indicated that turfgrass soils significantly accumulated SOC over time at depths of 0-2.5 cm (p<0.001), 2.5-5 cm (p<0.001), 5-10 cm (p<0.001) and 10-15 cm (p<0.001).

Slope of the nonlinear regression line indicated that the surface 2.5 cm of the soil sequestered SOC at a rate of 0.33% yr\(^{-1}\) and had the highest SOC concentration following initial sequestration of 8.4%. Soils at 2.5-5 cm and 5-10 cm depths sequestered SOC at maximum rates of 0.39% yr\(^{-1}\) and 0.31% yr\(^{-1}\) and reached SOC concentrations of 7.7% and 5.1%, respectively following initial sequestration. Finally, soils located at 10-15 cm depth, sequestered SOC at the lowest maximum rate of 0.21% yr\(^{-1}\) and had the lowest total SOC concentrations (3.8%) following initial sequestration. Samples at all depths initially sequestered SOC for an average of 19 years. Following this time period, SOC concentration stabilized or slightly decreased for approximately 40-50 years before resuming SOC sequestration approximately 60-70 years after lawn establishment.
Figure 2.2. The effect of home lawn turfgrass development on the soil organic carbon concentration at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over an 83 year period in Minneapolis, MN (One-way ANOVA, for interaction of SOC concentration by year at a depth of 0-2.5cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=7, N=3 for each sample year).

In contrast to soils located in Minneapolis, MN, those analyzed from Atlanta, GA had the lowest total SOC sequestration over time. Figure 2.3 shows the percent SOC sequestration following home lawn turfgrass establishment over a 93 year period at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm for home lawns in Atlanta, GA. The nonlinear regression spline analysis indicated that turfgrass soils throughout Atlanta
significantly accumulated SOC over time at depths of 0-2.5 cm (p<0.001), 2.5-5 cm (p<0.001), 5-10 cm (p<0.001) and 10-15 cm (p<0.001).

As was the case in Minneapolis, MN the surface 2.5 cm of the soil sequestered SOC at the highest rate, sequestering SOC at the maximum rate of 0.17% yr\(^{-1}\). The surface layer also had the highest initial SOC concentration of the four depths, with a total SOC concentration of 2.9%. Soils at 2.5-5 cm and 5-10 cm depths sequestered SOC at the maximum rates of 0.10% yr\(^{-1}\) and 0.08% yr\(^{-1}\) and reached SOC concentrations following initial sequestration of 1.7% and 1.2%, respectively. Finally, at 10-15 cm depth, soils sequestered SOC at the lowest maximum rate (0.05% yr\(^{-1}\)) and also contained the lowest SOC concentrations (1.0%). Samples at all depths initially sequestered SOC for an average of 12 years. Following this time period, SOC concentration stabilized for approximately 50-60 years before resuming SOC sequestration approximately 80-90 years after lawn establishment.
Figure 2.3. The effect of home lawn turfgrass development on the soil organic carbon concentration at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 93 year period in Atlanta, GA (One-way ANOVA, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=10, N=3 for each sample year).

Nonlinear regression analyses for the remaining 14 sites followed trends similar to those for Minneapolis, MN and Atlanta, GA (Appendix A). However, differences were observed between the maximum rate of SOC change, time for initial sequestration, and total SOC concentration following initial sequestration for soils in diverse regions.
At 0-2.5 cm depth, the maximum rates of SOC change ranged from 0.03% yr\(^{-1}\) in the soils of Seattle, WA to 0.70% yr\(^{-1}\) in San Francisco, CA, with an average maximum rate of SOC change for all locations of 0.22 ± 0.04% yr\(^{-1}\) (Table 2.3). The time for initial sequestration also varied by location, ranging from 13 years in Atlanta, GA, to 31 years in Duluth, MN and Wooster, OH. Mean time for initial sequestration for all locations was estimated at 18 years.
<table>
<thead>
<tr>
<th>Location</th>
<th>Max Rate of Soil Organic Carbon Change (% yr⁻¹)</th>
<th>Time for Initial Sequestration (yrs)</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>0.08</td>
<td>24</td>
<td>4.0 ± 0.4</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>0.17</td>
<td>13</td>
<td>2.9 ± 0.2</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>0.18</td>
<td>17</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>0.18</td>
<td>20</td>
<td>4.0 ± 0.1</td>
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<td>Denver, CO</td>
<td>0.19</td>
<td>20</td>
<td>6.0 ± 0.6</td>
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<td>Duluth, MN</td>
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<td>3.7 ± 0.2</td>
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<td>Houston, TX</td>
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<td>4.2 ± 0.1</td>
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<td>Las Vegas, NV</td>
<td>0.29</td>
<td>15</td>
<td>4.0 ± 0.2</td>
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<td>8.4 ± 0.3</td>
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<td>3.4 ± 0.3</td>
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<td>Phoenix, AZ</td>
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<td>3.5 ± 0.2</td>
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<td>2.8 ± 0.0</td>
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<td>San Francisco, CA</td>
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<td>6.1 ± 0.5</td>
</tr>
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<td>Seattle, WA</td>
<td>0.03</td>
<td>18</td>
<td>4.0 ± 0.2</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>0.27</td>
<td>13</td>
<td>4.1 ± 0.1</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>0.25</td>
<td>31</td>
<td>5.1 ± 0.2</td>
</tr>
<tr>
<td>Mean</td>
<td>0.21 ± 0.04</td>
<td>18</td>
<td>4.4 ± 0.3*</td>
</tr>
<tr>
<td>Range</td>
<td>0.03-0.70</td>
<td>13-31</td>
<td>2.8-8.4</td>
</tr>
</tbody>
</table>

*Indicates significance of p<0.05

Table 2.3. Maximum rate of soil organic carbon change, time for initial sequestration, and mean soil organic carbon concentration following initial sequestration for all sites sampled at a depth of 0-2.5 cm (One-way ANOVA, for interaction of mean SOC concentration following initial sequestration by site p<0.001, DF=350, N=12-30 for each sample site).

Mean SOC concentration in the surface 2.5 cm also varied among locations (p<0.001; Figure 2.4). Mean SOC concentrations ranged from 2.8% in the soils of Portland, ME, to 8.4% in those of Minneapolis, MN. Typically, soils nationwide sequestered SOC to concentrations between 3.5% and 4.5%. However, significantly high
SOC concentrations were observed in the soils of Denver, CO (6.0%), San Francisco, CA (6.1%), and Wooster, OH (5.1%), and significantly low concentrations of SOC were monitored in the soils of Atlanta, GA (2.9%). Specific interactions between sites can be observed in Table 2.4.

![Figure 2.4](image)

**Figure 2.4.** Mean soil organic carbon concentration following initial sequestration at a depth of 0-2.5 cm for 16 sites within the United States (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by location p<0.001, DF=15, N=18-27 for each city. Error bars = standard error; Results of individual interactions can be viewed in Table 2.8 to follow).
Soils at 2.5-5 cm depth exhibited trends similar to those observed in the surface 0-2.5 cm layer. The maximum rates of SOC change ranged from 0.01% yr\(^{-1}\) in Seattle, WA to 0.40% yr\(^{-1}\) in San Francisco, CA (Table 2.5). Especially high maximum rates of change were monitored in the soils of Minneapolis, MN (0.39% yr\(^{-1}\)), Orlando, FL (0.22% yr\(^{-1}\)), and Wooster, OH (0.20% yr\(^{-1}\)), with an average maximum rate of change for all locations of 0.15 ± 0.03% yr\(^{-1}\). Overall, the maximum rates of SOC change were lower than in the 0-2.5 cm depth. This interaction will be discussed at length later in
chapter 2. Time for initial sequestration ranged from 8 years in Cheyenne, WY to 43 years in the soils of Orlando, FL, with an average time for all locations of 18 years.

<table>
<thead>
<tr>
<th>Location</th>
<th>Max Rate of Soil Organic Carbon Change (% yr(^{-1}))</th>
<th>Time to Initial Sequestration (yrs)</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>0.05</td>
<td>24</td>
<td>2.8 ± 0.3</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>0.10</td>
<td>13</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>0.11</td>
<td>8</td>
<td>2.6 ± 0.2</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>0.06</td>
<td>23</td>
<td>2.4 ± 0.1</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>0.11</td>
<td>23</td>
<td>3.8 ± 0.6</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>0.14</td>
<td>23</td>
<td>3.3 ± 0.2</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>0.09</td>
<td>13</td>
<td>2.5 ± 0.1</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>0.19</td>
<td>13</td>
<td>2.7 ± 0.2</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>0.39</td>
<td>18</td>
<td>7.2 ± 0.3</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>0.22</td>
<td>43</td>
<td>2.7 ± 0.3</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>0.12</td>
<td>13</td>
<td>3.5 ± 0.2</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>0.06</td>
<td>10</td>
<td>2.3 ± 0.1</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>0.40</td>
<td>15</td>
<td>3.6 ± 0.3</td>
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<tr>
<td>Seattle, WA</td>
<td>0.01</td>
<td>15</td>
<td>2.8 ± 0.1</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>0.10</td>
<td>13</td>
<td>2.6 ± 0.1</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>0.20</td>
<td>23</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>Mean</td>
<td>0.15 ± 0.03</td>
<td>18</td>
<td>3.1 ± 0.2*</td>
</tr>
</tbody>
</table>

Range: 0.01-0.40 8-43 1.7-7.2

*Indicates significance of p<0.05

Table 2.5. Maximum rate of soil organic carbon change, time for initial sequestration, and mean soil organic carbon concentration following initial sequestration for all sites sampled at a depth of 2.5-5 cm (One-way ANOVA, for interaction of mean SOC concentration following initial sequestration by site p<0.001, DF=353, N=12-27 for each sample site).
Similar to the trend in the surface 2.5 cm, mean SOC concentration following initial sequestration at 2.5-5 cm depth showed variations with location (p<0.001; Figure 2.5). Mean SOC concentration ranged from 1.7% in the soils of Atlanta, GA, to 7.2% in those of Minneapolis, MN. Soils at all locations generally sequestered SOC to concentrations of 2.0% to 3.0%. However, as was the case in the surface layer, significantly high SOC concentrations were also observed in the soils of Denver, CO (3.8%), San Francisco, CA (3.6%), and Wooster, OH (3.8%). Variations in total mean SOC concentration within sites appeared less drastic than at the surface. For specific interactions between sites see Table 2.6.

Figure 2.5. Mean soil organic carbon concentration following initial sequestration at a depth of 2.5-5 cm for 16 sites within the United States (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by location p<0.001, DF=15, N=15-27 for each city. Error bars = standard error; Results of individual interactions can be viewed in Table 2.9 to follow).
Table 2.6. Interaction of mean soil organic carbon concentration by location at a depth of 2.5-5 cm (* Indicates significant difference of means at p<0.05)

*Indicates significance of p<0.05

At 5-10 cm depth, soils throughout diverse regions showed differences in the maximum rate of SOC change, time for initial sequestration, and mean SOC concentrations. The maximum rates of change ranged from 0.05% yr\(^{-1}\) in the soils of Denver, CO and Phoenix, AZ, to 0.31% yr\(^{-1}\) in the soils of Minneapolis, MN (Table 2.7).

Average maximum rate of SOC change was 0.13 ± 0.02% yr\(^{-1}\) nationwide. More than 50% of the soils analyzed for 5-10 cm depth had maximum rates of change of < 0.10% yr\(^{-1}\). The overall range of time for initial sequestration was the same as at 0-2.5 cm depth. Soils took just 8 years for initial sequestration in Atlanta, GA, and as long as 43 years for
Orlando, FL. Average time for initial sequestration for all locations was identical (18 years).

<table>
<thead>
<tr>
<th>Location</th>
<th>Max Rate of Soil Organic Carbon Change (% yr⁻¹)</th>
<th>Time to Initial Sequestration (yrs)</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>0.06</td>
<td>27</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>0.08</td>
<td>8</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>0.08</td>
<td>17</td>
<td>2.2 ± 0.1</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>0.09</td>
<td>23</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>0.05</td>
<td>23</td>
<td>2.7 ± 0.4</td>
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<tr>
<td>Duluth, MN</td>
<td>0.18</td>
<td>23</td>
<td>2.9 ± 0.2</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>0.08</td>
<td>13</td>
<td>1.8 ± 0.1</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>0.24</td>
<td>13</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>0.31</td>
<td>17</td>
<td>5.1 ± 0.3</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>0.10</td>
<td>43</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>0.05</td>
<td>13</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>0.06</td>
<td>11</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>0.21</td>
<td>11</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>0.09</td>
<td>15</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>0.11</td>
<td>15</td>
<td>2.2 ± 0.1</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>0.21</td>
<td>23</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td>Mean</td>
<td>0.13 ± 0.02</td>
<td>18</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td>Range</td>
<td>0.05-0.31</td>
<td>8-43</td>
<td>1.2-5.1</td>
</tr>
</tbody>
</table>

*Indicates significance of p<0.05

Table 2.7. Maximum rate of soil organic carbon change, time for initial sequestration, and mean soil organic carbon concentration following initial sequestration for all sites sampled at a depth of 5-10 cm (One-way ANOVA, for interaction of mean SOC concentration following initial sequestration by site p<0.001, DF=353, N=12-27 for each sample site).
The mean SOC concentration following initial sequestration ranged from 1.2% in Atlanta, GA, to 5.1% in Minneapolis, MN (Figure 2.6). Variation in mean SOC concentrations were attributed to location (p<0.001). However, range of SOC concentrations over location again decreased. Majority of soils at 5-10 cm depth sequestered SOC to concentrations of 1.8% to 2.8% with especially high SOC concentrations observed in Wooster, OH (3.3%). For specific interactions among sites at a depth of 5-10 cm depth see Table 2.8.

![Figure 2.6. Mean soil organic carbon concentration following initial sequestration at a depth of 5-10 cm for 16 sites within the United States (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by location p<0.001, DF=15, N=15-27 for each site. Error bars = standard error; Results of individual interactions can be viewed in Table 2.10 to follow).](image-url)
Soils at 10-15 cm depth followed trends similar to those for other depths. However, the maximum rates of SOC change at 10-15 cm depth were significantly lower than those monitored for other depths, and ranged from 0.04% yr\(^{-1}\) in Albuquerque, NM to 0.22% yr\(^{-1}\) in Las Vegas, NV (Table 2.9). Especially high maximum rates of change for 10-15 cm depth were also observed in the soils of Minneapolis, MN (0.21% yr\(^{-1}\)), with an average rate of change for all locations of 0.11 ± 0.01% yr\(^{-1}\). Time for soils to initially sequester SOC ranged from 13 years in Atlanta, GA to 43 years in Orlando, FL, with an average time for all locations of 18 years.

*Indicates significance of p<0.05

Table 2.8. Interaction of mean soil organic carbon concentration by location at a depth of 5-10 cm (* Indicates significant difference of means at p<0.05).
<table>
<thead>
<tr>
<th>Location</th>
<th>Max Rate of Soil Organic Carbon Change (% yr⁻¹)</th>
<th>Time to Initial Sequestration (yrs)</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>0.04</td>
<td>25</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>0.05</td>
<td>13</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>0.12</td>
<td>14</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>0.15</td>
<td>19</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>0.11</td>
<td>23</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>0.13</td>
<td>23</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>0.06</td>
<td>13</td>
<td>1.6 ± 0.1</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>0.22</td>
<td>13</td>
<td>2.2 ± 0.1</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>0.21</td>
<td>16</td>
<td>3.8 ± 0.3</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>0.07</td>
<td>43</td>
<td>1.2 ± 0.1</td>
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<td>Phoenix, AZ</td>
<td>0.11</td>
<td>11</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>0.05</td>
<td>10</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>0.11</td>
<td>11</td>
<td>1.5 ± 0.1</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>0.09</td>
<td>14</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>0.11</td>
<td>13</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>0.14</td>
<td>23</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>Mean</td>
<td>0.11 ± 0.01</td>
<td>18</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>Range</td>
<td>0.04-0.22</td>
<td>10-43</td>
<td>1.0-3.8</td>
</tr>
</tbody>
</table>

*Indicates significance of p<0.05

Table 2.9. Maximum rate of soil organic carbon change, time for initial sequestration, and mean soil organic carbon concentration following initial sequestration for all sites sampled at a depth of 10-15 cm (One-way ANOVA, for interaction of mean SOC concentration following initial sequestration by site p<0.001, DF=353, N=12-27 for each sample site).

The mean SOC concentration following initial sequestration at 10-15 cm depth varied among locations (p<0.001; Figure 2.7). The mean SOC concentrations ranged from 1.0% in the soils of Atlanta, GA, to 3.8% in those of Minneapolis, MN. The majority of soils at all locations sequestered SOC to concentrations of 1.5% to 2.3%. However, as was observed in the 0-2.5 cm depth, significantly high SOC concentrations
were observed in the soils of Wooster, OH (2.5%), and significantly lower SOC concentrations in Orlando, FL (1.2%). However, in contrast to other layers, especially high SOC concentrations were monitored in the soils of Duluth, MN (2.8%). Again, variations in mean SOC concentrations within sites appeared less drastic than at shallower depths. For specific interactions between sites see Table 2.10.

Figure 2.7. Mean soil organic carbon concentration following initial sequestration at a depth of 10-15 cm for 16 sites within the United States (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by location  p<0.001, DF=15, N=15-27 for each city. Error bars = standard error; Results of individual interactions can be viewed in Table 2.11 to follow).
Home lawn turfgrass soils through the U.S. showed significant differences in both the maximum rate of SOC change, time for initial sequestration, and mean SOC concentrations following initial sequestration (Table 2.11). To 15 cm depth, the maximum rates of SOC change ranged from 0.06% yr\(^{-1}\) in the soils of Albuquerque, NM to 0.36% yr\(^{-1}\) in those of San Francisco, CA. The average maximum rate of change for all 16 sites across the U.S. was 0.15 ± 0.02% yr\(^{-1}\). In addition to the soils in San Francisco, CA, high maximum rates of change were also monitored in the soils of Minneapolis, MN (0.31% yr\(^{-1}\)), Las Vegas, NV (0.24% yr\(^{-1}\)), and Wooster, OH (0.20% yr\(^{-1}\)).

Table 2.10. Interaction of mean soil organic carbon concentration by location at a depth of 10-15 cm (* Indicates significant difference of means at p<0.05).

<table>
<thead>
<tr>
<th></th>
<th>Albuquerque</th>
<th>Atlanta</th>
<th>Cheyenne</th>
<th>Dallas</th>
<th>Denver</th>
<th>Duluth</th>
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*Indicates significance of p<0.05
Additionally, the time for soils to initially sequester SOC varied by site, from 11 years in Atlanta, GA to 41 years in the soils of Orlando, FL, with an average time for all locations of 18 years.

<table>
<thead>
<tr>
<th>Location</th>
<th>Max Rate of Soil Organic Carbon Change (% yr(^{-1}))</th>
<th>Time to Initial Sequestration (yrs)</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)*</th>
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<tr>
<td>Albuquerque, NM</td>
<td>0.06</td>
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<td>2.7 ± 0.4</td>
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<td>Houston, TX</td>
<td>0.10</td>
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<td>2.3 ± 0.3</td>
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<tr>
<td>Las Vegas, NV</td>
<td>0.24</td>
<td>13</td>
<td>2.7 ± 0.2</td>
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<tr>
<td>Minneapolis, MN</td>
<td>0.31</td>
<td>18</td>
<td>5.6 ± 0.6</td>
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<tr>
<td>Orlando, FL</td>
<td>0.15</td>
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<td>2.0 ± 0.5</td>
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<td>Phoenix, AZ</td>
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<td>2.2 ± 0.5</td>
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<tr>
<td>Range</td>
<td>0.06-0.36</td>
<td>11-41</td>
<td>1.5-5.6</td>
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</table>

*Indicates significance of p<0.05

Table 2.11. Maximum rate of soil organic carbon change, time for initial sequestration, and mean soil organic carbon concentration following initial sequestration for all sites sampled at a depth of 0-15 cm (One-way ANOVA, for interaction of mean SOC concentration following initial sequestration by site p<0.001, DF=341, N=12-27 for each sample site).
Figure 2.8 shows the mean SOC concentrations of the entire soil profile analyzed (0-15 cm) for all 16 sites sampled in this study. The data show significant variation in the mean SOC concentration among locations (p<0.001; Figure 2.8, Table 2.11). Most sites had mean SOC concentrations of 2.0% to 3.0%. However, Minneapolis, MN has a significantly higher SOC, with a mean concentration of 5.6%. Wooster, OH, Denver, CO, and Duluth, MN, also had above average SOC concentrations with means of 3.4%, 3.2%, and 3.1%, respectively. Conversely, Atlanta, GA had significantly lower SOC concentrations following initial sequestration, with a mean concentration of 1.5%. Specific interactions among all sites can be visualized in Table 2.12.

Major differences in mean SOC concentration across sites is possibly due to a number environmental factors including MAT and MAP. Additionally, numerous soil properties such as $\rho_b$, nitrogen (N) concentration, and texture may also play a significant role in variation of SOC concentration. These factors are discussed at length in chapter 3.
Figure 2.8. Mean soil organic carbon concentration following initial sequestration at a depth of 0-15 cm for 16 sites within the United States (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of SOC concentration by location $p<0.001$, $DF=15$, $N=15-27$ for each city. Error bars = standard error; Results of individual interactions can be viewed in Table 2.7 to follow).
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*Indicates significance of p<0.05

Table 2.12. Interaction of mean soil organic carbon concentration by location at a depth of 0-15 cm ( * Indicates significant difference of means at p<0.05).

Additionally, mean SIC concentration was analyzed, and also varied in concentrations over a large spatial scale (p<0.001). The data in Fig. 2.9 displays the SIC concentrations at 0-15 cm depth for all sites sampled. The SIC concentrations varied largely among soils and sites. Especially high SIC concentrations were monitored in soils of Dallas, TX (2.2%) and Las Vegas, NV (2.1%), both having nearly 4 times as much SIC as the next closest location. Cheyenne, WY also has significant SIC concentrations at 0.6%, while Albuquerque, NM (0.3%), Phoenix, AZ (0.3%), and Houston, TX (0.2%) are characterized by minimal concentrations. As SIC is positively
correlated with MAT and negatively with MAP (Mi et al., 2008), these results are expected as some arid sites have high concentrations of SIC (Dallas, TX, Las Vegas, NV) because of relatively high MAT and low MAP.

Figure 2.9. Mean soil inorganic carbon concentration at a depth of 0-15 cm for 16 sites within the United States (One-way ANOVA with Tukey's post test for individual interactions, for interaction of mean SIC concentration by site p<0.001, DF=1751, N=84-132 for each sample site; Numbers with different letters are significantly different at p<0.05. Error bars = standard error).
**Depth Distribution and Soil Organic Carbon Sequestration:**

Soils analyzed showed variations in mean SOC concentration with increase in depth. The data in Fig. 2.10 shows the mean SOC concentration following initial sequestration for four separate depths in Minneapolis, MN, where SOC concentrations are the largest. The top 2.5 cm of the soil had significantly higher SOC concentrations (4.04%) than any other soil depth. The SOC concentration consistently decreased with increase in depth (p<0.001) and followed the order 2.5-5 cm (2.8%) > soils at 5-10 cm depth (2.5%) > soils at 10-15 cm depth (2.1%). However, while a trend for decreasing SOC concentration with depth can be observed, the differences between SOC concentration in the 5-10 and 10-15 cm depth was not significant at p<0.05.

![Figure 2.10](chart.png)

Figure 2.10. Mean soil organic carbon concentration following initial sequestration at 4 depths in Minneapolis, MN (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by depth p<0.001, DF=3, N=18 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Similar to the trend observed in the soils of Minneapolis, MN, those in Atlanta, GA, the site with the lowest mean SOC concentrations following initial sequestration, also followed a trend of decrease in SOC concentration with increase in depth (Figure 2.11). The surface 2.5 cm of the soil contained significantly higher SOC concentrations (2.9%) than any other soil depth. Decrease in SOC concentration with increase in depth followed the order 2.5-5 cm (1.7%) > soils at 5-10 cm depth (1.2%) > soils at 10-15 cm depth (1.0%). However, while a trend for decreasing SOC concentration with increase in depth is observed, differences in the three soil layers below 2.5 cm depth were not statistically significant at p<0.05.

Figure 2.11. Mean soil organic carbon concentration following initial sequestration at 4 depths in Atlanta, GA (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by depth p<0.001, DF=3, N=27 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Graphic plots of mean SOC concentration by depth show similar trends to those observed for Minneapolis, MN and Atlanta, GA (Appendix B). However, summary of the effect of depth on differences in the maximum rate of change in SOC concentration, time for initial sequestration, and mean SOC concentration following initial sequestration for all sites is shown in Table 2.13. The maximum rate of SOC change in all soils follows a trend of decreasing rate with increasing depth (p=0.001). Soil in the surface 2.5 cm of the profile sequestered SOC at a rate 0.12% faster than for 10-15 cm depth. This increase in the rate of SOC sequestration at the soil surface is likely due to the increased availability of plant nutrients. All home lawn turfgrasses analyzed received one yearly application of N fertilizer. While this fertilizer is able to illuviate into the sub soil over time, the surface layer can benefit from its application before it is leached into the sub-soil. Thus, increased N concentration in the soil may result in SOC pool enhancement over time, as is discussed in chapter 3. Additionally, the home lawns selected in this study were mowed regularly and all clippings were returned. Return of clippings also acts as an additional source of natural fertilizers which may further increase the overall N concentration in the surface layer. Finally, home lawns are generally mowed to a short maximum height. The weekly mowing can result in a limiting of the rooting depth and thus a much greater accumulation of root biomass is likely towards the soil surface (Shahba, 2010). As these roots decompose and release vital nutrients into the soil, they too may enhance stratification of the SOC in the surface layers.

Time for SOC concentrations to initially sequester SOC did not differ among depths (p=0.99). Soil depth did not significantly affect the length of time required for
home lawns to become SOC saturated. However, mean SOC concentrations following initial sequestration did differ among depths (p<0.001). The surface 2.5 cm depth had mean SOC concentrations 2.4% greater than for 10-15 cm depths. This decrease in mean SOC concentration with an increase in depth is also likely due to the same factors affecting the rate of change of SOC concentrations. Increased nutrient availability in the surface 2.5 cm due to fertilizer application, return of mowed grass clippings, and accumulation of root biomass in the surface are all likely the factors leading to an increase in SOC concentration in the soil surface.

The low SOC concentrations at deeper depths may prove beneficial to the overall SOC sink capacity of home lawns. As SOC concentrations at 10-15 cm depth were 125% lower than those at 0-2.5 cm depth, enhancement of SOC pool in deeper layers may hold the greatest potential for future C sequestration. Additionally, at deeper depths both the turnover time and chemical recalcitrance of SOM is increased, thus providing an environment for long term SOC deposition (Lorenz and Lal, 2005). In home lawns, the enhancement of SOC pool at deeper depths may be accomplished through the incorporation of deep rooting grasses, shrubs, and trees. This could provide greater inputs of OM directly to the sub soil. Additionally, maintaining soil conditions that maximize soil microbial communities as well as earthworm populations may allow OM to be illuviated to deeper depths before being stabalized.
<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Mean Max Rate of Soil Organic Carbon Change (% yr⁻¹)</th>
<th>Time for Initial Sequestration (yrs)</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5</td>
<td>0.22 ± 0.04(A)</td>
<td>18 (A)</td>
<td>4.4 ± 0.3 (A)</td>
</tr>
<tr>
<td>2.5-5</td>
<td>0.15 ± 0.03(AB)</td>
<td>18 (A)</td>
<td>3.1 ± 0.2 (B)</td>
</tr>
<tr>
<td>5-10</td>
<td>0.13 ± 0.02(B)</td>
<td>18 (A)</td>
<td>2.4 ± 0.2 (BC)</td>
</tr>
<tr>
<td>10-15</td>
<td>0.11 ± 0.01 (B)</td>
<td>18 (A)</td>
<td>1.9 ± 0.2 (C)</td>
</tr>
</tbody>
</table>

Table 2.13. Mean maximum rate of soil organic carbon change, time for initial sequestration, and mean soil organic carbon concentration following initial sequestration for all sites sampled at four separate depths. (One-way ANOVA with Tukey's post test for individual interactions, for interaction of max rate of SOC change by depth p=0.001, DF=60, N=16 for each depth; mean SOC concentration following initial sequestration by depth p<0.001, DF=60, N=16 for each depth; Numbers with different letters vertically are significantly different at p<0.05).

2.4 Conclusions

Upon conversion to home lawn turfgrass systems, soils have an SOC sink capacity over time. Samples obtained from all 16 sites at four depths significantly sequestered SOC following the establishment of home lawn turfgrasses. The majority of sites had SOC concentrations ~2-3%, with major variations in a select few locations. Exceptionally high concentrations of SOC were monitored in Minneapolis, MN where SOC concentrations were about double compared with the majority of other sites. Soils from Denver, CO, Duluth, MN, and Wooster, OH also had slightly higher SOC concentrations of above 3%. Additionally, soils from Atlanta, GA had significantly below average SOC concentrations, with mean SOC concentrations ~1.5%. Furthermore, SOC sequestration initially occurred for a period of ~18 years at all depths in all
locations, after which time SOC concentration stabilized for ~40-60 years before once again increasing. The overall time for initial sequestration varied by about 10 years within sites. However, no significant differences in initial SOC sequestration time was observed across spatial scales.

These results confirmed the initial hypothesis that U.S. home lawns have a potential to sequester SOC over time at various rates. Both the variation in SOC concentrations among sites and the time for initial sequestration are likely due to differences in climate and the attendant differences in soil properties. A closer look at these factors and their role in determining the SOC pool at each location are discussed in chapter 3.

In order to accurately determine the magnitude of SOC fluctuations across regions, differences in SIC concentrations were also monitored. Nationwide, variations in SIC concentration were observed with select locations indicating significant SIC concentrations. Soils from Las Vegas, NV, Dallas, TX, Cheyenne, WY, Phoenix, AZ, and Albuquerque, NM contained significant SIC concentrations. This trend was expected and is most likely due to the hot dry climates in which these sites are located. Sampling locations receiving ample rainfall and located within cooler climates showed little to no SIC concentration in home lawn turfgrasses.

Finally, a direct correlation between soil depth and SOC concentration was observed. As the depth of soil increased the SOC concentrations of the soil decreased. Following initial sequestration, the surface 2.5 cm of the soil profile in each site had mean SOC concentrations around 1.5% higher than in 10-15 cm depths. Additionally, the maximum rates of SOC change significantly decreased with increase in depth as
surface soils sequestered SOC at double the rates than in the 10-15 cm depth. Decrease in both maximum SOC sequestration rates and mean SOC concentrations following initial sequestration are expected due to the management of home lawn turfgrasses. Both the surface application of inorganic fertilizers as well as the fresh addition of aboveground biomass through grass clippings likely results in a higher concentrations of N and other nutrients in the soil surface. This increase in N concentration subsequently may increase mineralization of organic matter especially in the surface where application occurs. An in depth analysis and discussion of the interaction between soil N concentration and SOC concentration is presented in chapter 3.

References


Chapter 3: Effects of Climate and Soil Properties on Home Lawn Soil Organic Carbon Concentration and Pool

Abstract

A range of climatic factors and soil properties have significant effects on the soil organic carbon (SOC) concentration and pool to 15 cm depth in home lawn turfgrass systems throughout the United States. Soil sampling and analysis conducted nationwide indicated that increased mean annual temperature (MAT) was negatively correlated with SOC concentration. A SOC concentration decline of 3.3% was observed for each 1°C increase in MAT. Additionally, mean annual precipitation (MAP) showed a nonlinear interaction on SOC concentration with optimal levels in soils receiving 60 to 70 cm of MAP. In addition to climatic factors, soil properties also influenced SOC concentration. Soil nitrogen (N) concentration had a high positive correlation with SOC concentration, as 0.1% increase in N concentration led to a 0.99% increase in SOC concentration. Furthermore, soil bulk density ($\rho_b$) had a curvilinear interaction on SOC concentration, with an increase in $\rho_b$ indicating a positive effect on SOC concentration until a compaction of around 1.4-1.5 Mg m$^{-3}$ was attained, after which, inhibition of SOC sequestration occurred. Finally, no correlation between SOC concentration or pool was observed with texture. Based upon these results, optimal SOC pools are observed in regions of low MAT, moderate MAP, high soil N concentration, and moderate $\rho_b$. In order to maximize the C storage capacity of home lawns, non C-intensive management practices should be used to maintain soils within these conditions.

Keywords: Carbon Sequestration, Home Lawns, Climate, Soil Properties

3.1 Introduction

The effects of climate on soil organic matter (SOM) have been and remain a debatable topic. In a warming world, this theme is even more important because
increased global temperatures may release a substantial portion of the soil organic carbon (SOC) pool into the atmosphere as greenhouse gasses (GHG), thus providing a positive feedback to global temperature rise.

The SOC pool is negatively correlated with mean annual temperature (MAT) (Jenny, 1941; Post et al., 1982). At low temperatures, plant growth exceeds the SOC decomposition rates. However, as temperature increases, soil microbial activity also increases, leading to increased decomposition and emission of carbon dioxide (CO₂) (Jenkinson and Ayanaba, 1977; Lloyd and Taylor, 1994; Trumbore et al., 1996; Katterer et al., 1998; Holland et al., 2000; Dalias et al., 2001; Sanderman et al., 2003). Temperature and precipitation effects on SOC decomposition are now a topic of much debate (Giardina and Ryan, 2000; Knorr et al., 2005).

The effect of temperature on SOC decomposition may vary significantly across ecosystems. In forest ecosystems, while some research show a direct correlation of decreased SOC concentration with an increase in MAT (Fissore et al., 2008), others contend that differences in precipitation and temperature may have little or no effect at all (Giardina and Ryan, 2000). However, in grasslands, increased MAT decrease SOC concentrations (Burke et al., 1989).

The available literature indicate that the effects of temperature on SOC decomposition are highly variable. Additionally, much of the current research has come under scrutiny as the vast majority of studies are performed at the local level or utilize laboratory analysis only, thus limiting the interaction effects that may take place between temperature and a number of extraneous variables including mean annual precipitation (MAP) (Winkler et al., 1996; Niklinska et al., 1999). This observation provides much
justification into the need for studies that cover vast spatial areas under field conditions. These may be valid issues as interactions of temperature with precipitation as well as other soil physical properties may strongly affect the SOC pools.

In addition to the need for studies involving increased spatial variation, little research currently exists regarding the climatic effects on SOC pools in turfgrass ecosystems. While the research in grassland ecosystems support the hypotheses that increased MAT decrease the SOC pool (Burke et al., 1989), little research has been done on the vast area of turf that currently covers the nations landscape. The available research data has shown that net photosynthetic rate in turfs decreases as MAT increases above 30ºC (Al-Khatib and Paulson, 1999; Crafts-Brandner and Salvucci, 2000; Duff and Beard, 1974; Watschke et al., 1973; Xu and Huang, 2000a, 2000b, 2001). This decrease in growth is likely to result in decreased rates of SOC sequestration over time. Increases in MAT are also negatively correlated with turf quality, and root growth, both of which are negatively correlated with high soil temperatures (Pote et al., 2006; Xu and Huang, 2001). This decrease in turf quality may also have a significant adverse effect on SOC pools in turfgrasses.

Similar to the MAT, the effects of MAP on SOC pools are also debatable. In general, increase in MAP enhances SOC concentration (Jenny, 1941; Post et al., 1982; Amelung et al., 1997). The scarcity of vegetation and biomass in dry soils is responsible for low SOC concentrations (Jenny, 1941). Yet, the context of the MAP may have significant effects on SOC pools. For instance, in agricultural ecosystems, an increase in MAP decreases the SOC concentration (Marton, 2008). In contrast, Burke et al. (1989), utilizing the data of over 500 grassland soils and 300 cultivated soils, observed that
grassland soils show an increase in SOC concentration with increase in MAP. However, SOC losses due to cultivation are increased with increase in MAT, indicating that increases in MAP lead to SOC sequestration in undisturbed lands, but losses of SOC concentration increase over time with change in land use.

Even in undisturbed ecosystems, the amount of MAP may affect SOC concentration. Shen et al. (2008) reported that MAP in drylands of the southwest United States is positively correlated with SOC concentration. The low levels of available water limit plant growth, and increases in water availability increase plant growth and enhance SOC pools. However, in wetter regions, increased MAP can decrease SOC concentrations. Derner and Schuman (2007) reported that in the surface 10 cm layer, soils receiving less than 43.9 cm of MAP increase SOC storage with further increases in MAP. However, once this threshold MAP has been attained, there is a decrease in SOC pools with further increase in MAP. These results show the immense complexity regarding SOC dynamics in relation to water regime.

Similarly to MAT, a little research has been done on the effects of MAP on SOC sequestration in turfgrasses. In general, irrigation of turfgrasses positively affects turf quality, especially in arid and semi-arid regions (Qian and Engelke, 1999). However, effect of MAP and irrigation may also differ among grass species. Sifers et al. (1990) reported that drought resistance varies among grass species, Zoysiagrass having the highest tolerance and St. Augustine (Stenotaphrum secundatum) the lowest. Carow (1996) reported that Bermuda (Cynodon dactylon) and St. Augustine grass species have strong and Zoysiagrass weak drought avoidance. Qian et al. (1997) observed an all together different trend of drought avoidance among species. Differences in response of
grass species to water availability may depend on numerous interactive climatic conditions (Carow, 1996). Furthermore, precipitation also affects physical properties and soil forming factors (Jenny, 1941), which may play critical roles in the development of turf soils and their responses to changes in MAT and MAP.

The importance of variations in SOC concentration due to climatic differences in turfgrass soils may have numerous implications. If a direct correlation can be ascertained between SOC concentration and the climate factors (i.e., MAT and MAP), this would provide vital information into utilizing turf species to sequester atmospheric CO₂ and mitigate global climate change (GCC). If it can be shown that SOC concentration is maximized within certain climates and minimized in others, turf proliferation could be avoided in the latter and concentrated in the former. This strategy would allow for greater sequestration potential for a land use type that is increasing dramatically with population growth and urbanization.

In addition to climatic variables, specific soil properties can also directly impact the SOC sequestration potential of soils. Soil parameters such as texture, pH, and bulk density ($\rho_b$) determine formation of stable aggregates and effectively sequester SOC. One such soil property is soil nitrogen (N), which may have a significant effect on SOC concentrations. Many studies have shown a direct correlation between soil N concentrations and SOC concentrations. Numerous reasons have been suggested for this correlation including that an increase in soil N concentration can lead to drastically decreases litter decomposition and soil respiration, thus increasing the mean residence time (MRT) of SOC (Franklin et al., 2003). Other researchers have hypothesized that increases in soil N concentration decrease rates of SOC decomposition, thus leading to
SOC enrichment (Hyvonen et al., 2008; Magnani et al., 2007). In either case the increased soil N increases the SOC pool. The available research data has suggest that SOC sequestration potential in forest ecosystems may be directly driven by N deposition (Magnani et al., 2007; Kahle et al., 2008). Such increases in the SOC pool in forest and other ecosystems may prove significant, as anthropogenic N increases have been responsible for an estimated net SOC storage of between 0.1 and 0.3 Pg C yr\(^{-1}\) in the terrestrial ecosystem (Townsend et al., 1996; Vitousek et al., 1997). Such a correlation is also reported for grassland ecosystems, because increased N deposition in grasslands increases rates of SOC mineralization (Hopkins et al., 2011). If this correlation holds true for turfgrass ecosystems, it may prove to be an especially important factor in the SOC sequestration rate and potential of these systems as they often receive annual inputs of inorganic N through chemical fertilizers. In conjunction with other climatic and soil properties, increased N inputs may be a valuable factor in determining the SOC sequestration potential of turfgrass systems throughout the country.

Soil texture can also strongly impact the SOC pool, especially the clay content which determines the magnitude of SOC storage (Tron et al., 1997). Synthesis of data of over 800 soils showed that increase in clay content is positively correlated with SOC concentration (Burke et al., 1989). In some cases, however, clay content may not be correlated with SOC concentration in grassland ecosystems (Percival et al., 2000). Yet, the proportion of fine particles (silt plus clay) has a strong effect on the SOC sink capacity (Oades, 1988; Carter, 1996; Hassink, 1997). Once the fine particles have become saturated, however, coarse particles can also retain additional SOC (Carter et al., 2003; Tsutsuki and Kuwatsuka, 1990), and coarse particles can account for as much as
40% of the total SOC content (Carter et al., 2003; Kay, 1998; Yang and Kay, 2001). With such a large variation in SOC storage, numerous climatic, physical, and chemical properties interactively affect the overall sequestration of SOC.

Soil $\rho_b$ also impacts the SOC pools. Compacted layers with high density limit addition of fresh organic matter (OM) to the soil and decrease SOC storage (Brevik et al., 2002). Thus, reduction in soil $\rho_b$ may increase the SOC pool and increase sequestration. This scenario is especially promising for turf soils, which are treated with coring to alleviate compaction. Decrease in compaction and improved grass growth increase the SOC pool (Golubiewski, 2006).

Soil inorganic carbon (SIC) concentration also varies across climatic regions and with depth, as accumulation occurs when carbonates are dissolved, leached and then reformed. These processes are important to soil SOC sequestration, because leaching of SIC into groundwater may be a major mechanism of SOC sequestration, equivalent to about 1 Mg C ha$^{-1}$ yr$^{-1}$ (Wilding, 1999). The SIC pools are the largest in hot and dry soils where water is scarce and temperatures are high (Mi et al., 2008). This scenario is important to turfgrass systems as the proliferation of turfs in hot dry climates continues to increase. The increased development of golf courses and home lawns in areas of the southwest United States strongly increases the possibility of high SIC sequestration.

Furthermore, soil acidity may also affect the SOC pools. Soil pH impacts exoenzyme activities during litter decomposition (Kok and Vandervelde, 1991; Griffith et al., 1995; Walse et al., 1998; Spiegelberger et al., 2006). Dramatic effects on litter decomposition could dramatically alter SOC pools in diverse regions. In addition, if microbial activity is slowed in selected soils due to variations in acidity, SOC
sequestration may increase with the decrease in microbial decomposition. For these reasons, soil pH may be a significant factor affecting the SOC sequestration potential of turfgrass soils. Increased use of inorganic fertilizers, pesticide application, and other maintenance practices may alter the acidity of the soil and subsequently change the SOC sequestration. In addition, if pH is an important factor in determining SOC sequestration rates, areas of the country where pH may lead to high microbial decomposition and subsequent low SOC sequestration may not be converted to turfgrass proliferation in lieu of other more C-positive land use practices.

Finally, grass species may have a significant impact on SOC sequestration. While species of grasses are chosen due to their growing capabilities and characteristics in various climatic regions, often non optimal species are planted to receive a desired appearance. Whether or not different species sequester greater amounts of SOC depends on a number of soil and climatic factors. However, the effect of these properties may be exacerbated by the grass species. For example, drought resistance in turfgrasses varies greatly among species (Stifers et al., 1990; Carow, 1996; Qian et al., 1997). Furthermore, different species exhibit drought tolerance over different conditions. Thus, even slight variations in climate and soil properties may greatly affect the success of a turfgrass species. Greater drought tolerance could enhance SOC sequestration (Qian et al., 1997).

This chapter assesses the relationship between key soil properties and climatic variables and the SOC sink capacity of U.S. home lawns. Based on the previous literature, both SOC pool and rates of SOC sequestration in home lawns nationwide are predicted to increase with increases in soil clay content and acidity. Furthermore, it is hypothesized that increases in SOC pool and rates of SOC sequestration occur with
decreases in MAT and increases in MAP. While climatic variables (i.e., MAT and MAP) as well as soil properties (i.e., acidity and texture) may have significant influences on the SOC sequestration of turfgrasses, they likely interact with one another. For this reason it is important to assess turfgrass SOC sequestration over a significant spatial area in order to determine the possible interactions of such variables and the capacity of various turfgrass species to sequester SOC over time.

3.2 Materials and Methods

Site description:

See materials and methods in chapter 2 for complete site description.

Experimental Design:

Nine soil samples were obtained from each lawn and native sampling site within each site. Each yard was separated into 3 parts to account for variations in slope, shade, etc. Three samples were obtained from each of the three subdivided sections. All samples were taken at least 3 meters from the actual home and from any trees located within the yard. Three samples were used for the determination of total C (%), and pH for 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm depths. In addition, three cores were utilized for the determination of \( \rho_b \), and three for textural analysis.

Soil Sampling and Analyses:
All soil samples were obtained between October 1, 2009 and October 1, 2010. At each home lawn site, nine core samples were obtained to 15 cm depth using 5.4 cm (2 inch) diameter PVC pipe. Pipes were driven into the ground using a rubber mallet to a 15 cm depth and extracted, as an intact soil core.

Six intact cores were removed from the PVC by forcing through one end, allowing for removal from the pipe. The cores were then divided into four sections in the following depth increments: 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm. Soil was air dried, gently ground using a wooden roller, sieved through a 2 mm sieve and all remaining litter and root material were collected separately. Samples from three of the cores were then analyzed for textural analyses and determination of silt, clay, and sand contents by the hydrometer method (Gee and Or, 2002).

Samples from the other three cores were also separated by depth and then further ground and sieved through a 0.125 mm sieve, placed in 10 ml vials containing two stirring magnets and ball-milled for 24 hours. A subsample of the finely ground soil was used to determine total soil carbon (TSC) for each site and four separate depths using the dry combustion method with an NC 2100 soil analyzer (ThermoQuest CE Instruments, Milan, Italy). A second subsample of the finely ground soil was then mixed with deionized water in a 1:1 solution and the pH was determined using a pH meter (USDA, 1996). For samples with a pH<7.5, TSC was assumed to be SOC (Bohn and McNeal, 1985). For those with a pH>7.5, a third subsample of the finely ground sample was treated with 0.1N hydrochloric acid to determine concentration of SIC (Kennedy et al., 2005). Total SIC was subtracted from the TSC determined by the dry combustion method to determine the SOC concentration in each sample. Samples from the final three
cores were not divided into separate depths. These were utilized for the determination of \( \rho_b \) using the core method (Blake and Hartage, 1986).

**Soil Organic Carbon Pool Determination:**

The data on SOC concentration was plotted against the years since turfgrass development for all sites at each depth. Using SAS Statistical Procedures (SAS Institute Inc., 1994), a nonlinear regression analysis was performed on each plot to determine the initial amount of SOC sequestered per year per site per depth, as well as the time needed for soil initial SOC concentration to stabilize (8-43yrs). The overall initial SOC sequestered per site was then determined by using the following formulae: (Eqs. 1-3)

\[
10^4 \text{(m}^2/\text{ha}) \times \text{depth(m)} \times \rho_b \text{ (Mg/m}^3\text{)} \times \text{C seq/yr(\%)} /100 = \text{Mg C seq/ha/yr} \quad \ldots \quad \text{(Eq. 1)}
\]

\[
\text{Mg C/ha} \times \text{ha} = \text{Mg C seq per site} \quad \ldots \quad \text{(Eq. 2)}
\]

\[
\text{Mg C seq per site} \times \text{years of initial sequestration} = \text{Total Mg C seq per site} \quad \ldots \quad \text{(Eq. 3)}
\]

Using the \( \rho_b \) determined from each lawn and percent SOC sequestered per year at each depth as previously determined, the Mg of C sequestered per hectare per year was determined using Eq. 1. Multiplication of this result by the area of home lawn turfgrass in question provides the total amount of SOC sequestered per year in Mg over a specific area (Eq. 2). Further multiplication of this result by the number of years of sequestration until SOC concentrations stabilized estimates the overall potential of a home lawn to sequester SOC over the time frame desired (Eq. 3).
Statistical Analysis:

Minitab 15 was utilized to run regression analysis of SOC concentration (%) following initial sequestration for temperature, heating degree days, cooling degree days, precipitation, pH, soil N concentration, clay content, silt content, silt plus clay content, and $p_b$ to determine single correlations. The 30 year average for MAT, number of heating degree days (HDD), and number of cooling degree days (CDD), at each sampling site was taken from NOAA's National Climatic Data Center (NOAA, 2011). NOAA HDD are determined from the summations of negative differences between the mean daily temperature and 65ºC. Likewise, CDD are determined from the summations of positive differences between the mean daily temperature and 65ºC. Separate analysis was done for multiple regressions to determine interactions among variables. Additionally, One way ANOVA's with Tukey's post tests were utilized to determine the interaction between SOC concentration, pool, and numerous variables. The data were used to plot 3-D surface and contour plots to determine relationships between MAT, MAP, and SOC concentration (%) after initial sequestration. Finally, best subsets and multiple regressions were utilized for estimation of SOC concentration and pool based upon climatic variables and soil properties.

3.3 Results and Discussion

Soil Organic Carbon Concentration and Pool in U.S. Home Lawns:

While all turfs analyzed significantly sequestered SOC following the establishment of home lawns, mean SOC concentration varied across the U.S. (p<0.001;
Table 3.1). The SOC concentrations following initial sequestration ranged from 1.5% in the soils of Atlanta, GA, to 5.6% in Minneapolis, MN. Average SOC concentration across all sites was 2.7%. In addition to the soils located within Minneapolis, MN, especially high SOC concentrations were observed in Wooster, OH (3.4%), Denver, CO (3.2%), and Duluth, MN (3.1%). For all other soils analyzed, SOC concentrations were between 2% to 3%. Similar to SOC concentration, SOC pool also varied among sites (p<0.001; Table 3.1). Average SOC pool for all sites was 59.8 Mg C ha\(^{-1}\). Across all sites, however, the SOC pool ranged from 34.9 Mg C ha\(^{-1}\) in the soils of Atlanta, GA, to 125.5 Mg C ha\(^{-1}\) in Minneapolis, MN. The SOC pool in most home lawn soils in the U.S. ranged between 45 and 65 Mg C ha\(^{-1}\). However, in addition to the soils of Minneapolis, MN, high SOC pools were observed in soils of Wooster, OH (74.3 Mg C ha\(^{-1}\)) and Duluth, MN (69.4 Mg C ha\(^{-1}\)). Conversely, an exceptionally low SOC pool was observed in soils of Portland, ME (42.1 Mg C ha\(^{-1}\)).

Home lawn turfgrasses across the U.S. have a significant SOC sink capacity. However, SOC sequestration varies across sites. These variations are likely based on differences in climatic and soil properties across regions. Furthermore, differences in SOC sequestration may be influenced by the particular grass species optimally grown within certain locations.
<table>
<thead>
<tr>
<th>City</th>
<th>Mean Soil Organic Carbon Concentration Following Initial Sequestration (%)*</th>
<th>Mean Soil Organic Carbon Pool Following Initial Sequestration (Mg C ha$^{-1}$)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>2.7 ± 0.4</td>
<td>62.7 ± 8.6</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>1.5 ± 0.4</td>
<td>34.9 ± 8.9</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>2.5 ± 0.4</td>
<td>51.8 ± 6.9</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>2.5 ± 0.2</td>
<td>51.8 ± 3.8</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>3.2 ± 0.8</td>
<td>65.7 ± 16.0</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>3.1 ± 0.4</td>
<td>69.4 ± 8.7</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>2.3 ± 0.3</td>
<td>48.3 ± 6.0</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>2.7 ± 0.2</td>
<td>62.3 ± 4.1</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>5.6 ± 0.6</td>
<td>125.5 ± 12.9</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>2.0 ± 0.5</td>
<td>46.6 ± 8.0</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>2.2 ± 0.5</td>
<td>46.6 ± 11.5</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>2.2 ± 0.2</td>
<td>42.1 ± 5.8</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>2.5 ± 0.3</td>
<td>51.4 ± 5.7</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>2.7 ± 0.5</td>
<td>65.5 ± 11.9</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>2.5 ± 0.1</td>
<td>57.6 ± 1.1</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>3.4 ± 0.5</td>
<td>74.3 ± 10.0</td>
</tr>
<tr>
<td>Mean</td>
<td>2.7 ± 0.4</td>
<td>59.8 ± 8.9</td>
</tr>
<tr>
<td>Range</td>
<td>1.5-5.6</td>
<td>34.9-125.5</td>
</tr>
</tbody>
</table>

*Indicates significant difference at p<0.05

Table 3.1. Mean soil organic carbon concentration and pool following initial sequestration to 15 cm depth for 16 sites sampled in this study (One Way ANOVA with Tukey's post test for interactions among sites, for interaction of SOC concentration and pool by site p<0.001, DF=341, N=12-27 for each location).

**Effect of Temperature on Soil Organic Carbon Concentration and Pool:**

Following initial sequestration, concentrations of SOC in home lawn turfgrass systems indicated significant differences among sites of divergent temperatures.

Regression analyses of SOC concentration over a range of MAT for four separate depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated a decline in SOC concentration with
an increase in ambient temperature (p<0.001; Figure 3.1). In the surface 2.5 cm depth, increased MAT initially resulted in slight gains of SOC. However, further increase in MAT decreased SOC concentration. Rates of SOC change with increase in MAT are similar for all other depths, ranging from 3.2% °C⁻¹ increase at 2.5-5 cm depth to 5.5% in the 10-15 cm depth.

Figure 3.1. The effect of mean annual temperature on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and temperature for all depths p<0.001, DF=353, N=354).
Similarly, regression analysis of SOC concentration over a range of MAT for the entire soil profile (0-15 cm) indicated significant decreases in SOC concentration (p<0.001) under high temperature regimes (Figure 3.2). For 0-15 cm depth, SOC concentration decreased 3.3% for each 1°C increase in the MAT. Thus, MAT may have a significant effect on U.S. home lawn soils located in vastly different temperature regimes.

![Figure 3.2](image)

Figure 3.2. The effect of mean annual temperature on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and temperature p<0.001, DF=341, N=342).
The average SOC concentration for all data collected ranged from 3.1% for MAT of 4°C to 2.2% for 23°C. Notably high SOC concentrations are measured in soils corresponding with MAT of 7°C (3.9%) and 10°C (3.3%). In contrast, low SOC concentrations are measured in soils located in sites with a MAT of ≥ 17°C (1.5%) (Figure 3.3).

Figure 3.3. The effect of mean annual temperature on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by temperature p<0.001, DF=341, N=342, means with different letters are significantly different at p<0.05).
The SOC pool to 15 cm depth also declined with increase in MAT (p<0.001; Figure 3.4). The average rate of SOC pool decline with increase in MAT was 3.1% for each 1°C increase in MAT. This equates to a decrease in 2.6 Mg C ha\(^{-1}\)°C\(^{-1}\). Thus, SOC pool may be drastically altered by the MAT of a site. For sites with a difference in MAT of 20°C, there was a difference in SOC pool of 34.2 Mg C ha\(^{-1}\).

![Figure 3.4](image)

Figure 3.4. The effect of mean annual temperature on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and temperature p<0.001, DF=341, N=342).
The mean SOC pool for all sites ranged from 69.4 Mg C ha\(^{-1}\) for a MAT of 4\(^\circ\)C to 47.1 Mg C ha\(^{-1}\) for 23\(^\circ\)C. Especially high SOC pools were computed for sites with MAT of 7\(^\circ\)C (85.8 Mg C ha\(^{-1}\)) and 10\(^\circ\)C (70.3 Mg C ha\(^{-1}\)). In contrast, low SOC pools were computed for sites with MATs of ≥ 17\(^\circ\)C (34.9 Mg C ha\(^{-1}\)) (Figure 3.5).

Figure 3.5. The effect of mean annual temperature on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by temperature p<0.001, DF=341, N=342, means with different letters are significantly different at p<0.05).
The SOC concentration following initial sequestration in home lawn turfgrass systems was also compared in the context of annual HDD and CDD to assess the temperature effects. Use of HDD and CDD may be advantageous over the MAT because these parameters encompass major yearly fluctuations in temperature within a site. Further, HDD and CDD allow for separate comparison among sites which may have similar MATs but wide annual temperature fluctuations.

The SOC concentrations following initial sequestration in home lawn turfgrass systems were significantly influenced by CDD. Regressions for 4 depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated decline in SOC concentration with increase in CDD (p<0.001; Figure 3.6). However, rates of change in SOC concentration with increase in CDD were similar among depths and ranged from 0.008% decrease in SOC per degree day in the surface 2.5 cm depth to a 0.02% decrease in SOC concentration for the 5-15 cm depth.
Figure 3.6. The effect of number of mean annual cooling degree days on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and CDD for all depths p<0.001, DF=353, N=354).

Similarly, regression analysis of SOC concentration over a range of CDD for the entire soil profile (0-15 cm) indicated a significant decrease in SOC (p<0.001) under high temperature conditions (Figure 3.7). For 0-15 cm depth, the SOC concentration decreased by 0.02% per unit increase in CDD.
The mean SOC concentration for all data ranged from 3.1% in soils with CDD of 0-400 to 2.4% in those with 2000-2400 degree days. Notably high SOC concentrations were observed in soils corresponding to CDD of 0-400 degree days (3.1%), and low SOC concentrations were measured in those corresponding to 800-1200 degree days (1.9%) (Figure 3.8).
Figure 3.8. The effect of number of mean annual cooling degree days on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration m to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by CDD p<0.001, DF=341, N=342, means with different letters are significantly different at p<0.05).

The SOC pool to 15 cm depth also declined with increase MAT (p<0.001; Figure 3.9). Total SOC pool declined by 0.009 Mg C ha\(^{-1}\) per unit increase in CDD. This is equivalent to a 0.01% change in SOC pool per unit change in CDD.
Figure 3.9. The effect of number of mean annual cooling degree days on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and CDD p<0.001, DF=341, N=342).

The mean SOC pool for all data ranged from 67.1 Mg C ha\(^{-1}\) in soils corresponding to CDD of 0-400 to 47.6 Mg C ha\(^{-1}\) for those with a CDD of 2000-2400. Along with soils located in regions corresponding to CDD of 0-400, notably high SOC pools were observed in soils with a CDD of 400-800 (62.7 Mg C ha\(^{-1}\)), and low in those with 900-2400 CDD (Figure 3.10).
Figure 3.10. The effect of number of mean annual cooling degree days on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey’s post test for individual interactions, for all interactions of SOC pool by CDD p<0.001, DF=341, N=342, means with different letters are significantly different at p<0.05).

The SOC concentrations following initial sequestration in home lawn turfgrass systems indicated significant differences among sites with differences in HDD.

Regressions of SOC concentration for a range of HDD and four separate depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated a decline in SOC with increase in number of HDD (p<0.001; Figure 3.11). Rates of SOC concentration change with increase change in HDD were similar among four depths and range from a 0.03% change in SOC
concentration per unit change in HDD in the 0-2.5 cm depth to 0.005% change for 10-15 cm depth.

Figure 3.11. The effect of number of mean annual heating degree days on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and HDD at all depths p<0.001, DF=350, N=351).

Similarly, regression analysis of SOC concentration over a range of HDD for the 0-15 cm depth indicated significant decrease in SOC (p<0.001) with increase in HDD.
(Figure 3.12). For 0-15 cm depth, SOC concentration increased by 0.02% per unit increase in HDD.

![Figure 3.12. The effect of number of mean annual heating degree days on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and HDD p<0.001, DF=350, N=351).](image)

The mean SOC concentration of all data ranged from 2.2% in soils for HDD < 1000 HDD to 3.1% for those with HDD of 5000-6000. In addition to soils corresponding to HDD of 5000-6000, notably high SOC concentrations were observed in soils with
HDD of 3000-4000 (3.3%) and 4000-5000 annual HDD (3.4%), and low for those with HDD of < 1000 (2.2%), 1000-2000 (2.3%) and 2000-3000 (2.6%) (Figure 3.13).

The SOC pool to 15 cm depth also increased with increase in number of annual HDD (p<0.001; Figure 3.14). The SOC pool changed 0.01% per unit change in HDD. This is equivalent to a 0.005 Mg C ha\(^{-1}\) change per unit change in HDD with the addition
of 1 HDD. Based on these data, soils located in regions differing by 5000 HDD will differ in SOC pool by 20.99 Mg C ha\(^{-1}\).

![Graph showing the effect of number of mean annual heating degree days on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and HDD p<0.001, DF=350, N=351).](image)

Figure 3.14. The effect of number of mean annual heating degree days on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and HDD p<0.001, DF=350, N=351).

The mean SOC pool for all data ranged from 47.5 Mg C ha\(^{-1}\) in soils with a HDD < 1000 to 69.4 Mg C ha\(^{-1}\) for measured HDD of 5000-6000. Notably high SOC pools were measured in soils with HDD of 3000-4000 (70.0 Mg C ha\(^{-1}\)), 4000-5000 (73.1 Mg C ha\(^{-1}\)).
ha$^{-1}$) and 5000-6000 (69.4 Mg C ha$^{-1}$). In contrast, low SOC pools were observed in soils with < 1000 HDD (47.5 Mg C ha$^{-1}$) and 1000-2000 HDD (53.6 Mg C ha$^{-1}$) (Figure 3.15).

Figure 3.15. The effect of number of mean annual heating degree days on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by HDD $p<0.001$, DF=350, N=351, means with different letters are significantly different at $p<0.05$).

High variability in SOC concentration was observed among all sites. Regressions of SOC concentration versus MAT for 0-2.5 cm, 2.5-5 cm, and 5-10 cm, and 10-15 cm depth indicated $R^2$ of 0.05, 0.10, 0.15 and 0.18, respectively. Similarly, high variation
was observed in the regressions for SOC concentration ($R^2=0.14$) and SOC pool ($R^2=0.13$) versus MAT to 15 cm depth. Likewise, regressions of SOC concentration at 0-2.5 cm, 2.5-5 cm, 5-10 cm and 10-15 cm versus CDD indicated $R^2$ of 0.13, 0.14, 0.15 and 0.14, respectively. High variation was also observed in regressions for both SOC concentration ($R^2=0.07$) and SOC pool ($R^2=0.06$) versus CDD to 15 cm depth. Similar to CDD, HDD was also highly variable among sites. Regressions of SOC concentration versus HDD at 0-2.5 cm, 2.5-5 cm, 5-10 cm and 10-15 cm indicated $R^2$ of 0.05, 0.10, 0.15, and 0.18, respectively. Similarly, high variation was observed in the regressions for both SOC concentration ($R^2=0.14$) and SOC pool ($R^2=0.13$) to 15 cm depth versus HDD.

The high variation discussed above may be attributed to two factors. The first factor is the limited number of samples obtained. While the data contains an n value of ~350, these are spread among 16 different sites for 10 different temperature regimes. Therefore, each temperature regime comprises 35 data points. While this is sufficient to calculate the interaction between temperature regime and SOC concentration and pool, the variability may be decreased, and the subsequent interaction of SOC and MAT increased through the acquisition of more sampling sites and data analyses. Secondly, SOC concentration is also affected by a number of other soil physical and chemical properties as well as a range of climatic factors (i.e., MAP). The interaction of these factors in addition to the effects of MAT are likely the cause of a high variation. The interaction between additional climatic and soil properties is discussed at length throughout the remainder of this chapter.

Regardless of these confounding variables, the data support the hypothesis that SOC concentration and pool increase with decrease in MAT. Based on these results, it is
likely that at low temperatures, home lawn biomass growth exceeds SOC decomposition rates. However, as MATs increase, soil microbial activity may also increase, subsequently accelerating rates of SOC decomposition and releasing SOC as CO$_2$.

**Effect of Precipitation on Soil Organic Carbon Concentration and Pool:**

The MAP may have positive or negative effects on SOC concentration depending on soil and land use. Results presented herein show that the SOC concentrations following initial sequestration in home lawn turfgrass systems differed significantly because of differences in MAP. Regressions of SOC concentration over a range of MAP at four depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated an initial increase in SOC concentration with an increase in MAP, followed by a decrease in SOC concentration after a threshold precipitation (p<0.001; Figure 3.16). For all four depths, increase in SOC concentration due to increase in MAP occurred for the first 70 cm per year. Any subsequent increase in MAP decreased the overall SOC concentration.
Figure 3.16. The effect of mean annual precipitation on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and precipitation at all depths p<0.001, DF=350, N=351).

Similarly, regression analysis of SOC concentration over a range of MAP for 0-15 cm depth indicated an increase in SOC concentration with an increase in MAP, followed by a decrease in SOC concentration after a threshold precipitation (p<0.001; Figure 3.17). Increase in SOC concentration occurred at 0-15 cm depth with increased precipitation until MAP reached approximately 65 cm yr$^{-1}$. Additional MAP beyond 65 cm yr$^{-1}$ significantly decreased SOC concentration.
Figure 3.17. The effect of mean annual precipitation on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and precipitation p<0.001, DF=350, N=351).

Mean SOC concentrations for all data ranged from 2.7% for MAP of 11 cm yr\(^{-1}\) to 1.5% for 141 cm yr\(^{-1}\), with notably high SOC concentrations for 75 cm yr\(^{-1}\) (5.6%). Conversely, low SOC concentrations are observed in soils located at a MAP of 141 cm yr\(^{-1}\) (1.5%), 123 cm yr\(^{-1}\) (2.0%), 116 cm yr\(^{-1}\) (2.0%), 122 cm yr\(^{-1}\) (2.3%), 21 cm yr\(^{-1}\) (2.4%), and 39 cm yr\(^{-1}\) (2.5%) (Figure 3.3).
Figure 3.18. The effect of mean annual precipitation on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by precipitation $p<0.001$, DF=341, N=342, for interactions between sites see table 3.2).
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*Indicates significance of p<0.05

Table 3.2. Interaction of mean soil organic carbon concentration by mean annual precipitation at a depth of 0-15 cm (* Indicates significant difference of means at p<0.05).

The SOC pool to 15 cm depth also indicated an initial increase in pool with an increase in MAP, followed by a decrease after the threshold precipitation (p<0.001; Figure 3.19). As was observed for SOC concentrations, SOC pool increased until MAP reached approximately 65 cm yr⁻¹. Additional precipitation beyond the 65 cm yr⁻¹ threshold significantly decreased the SOC pools nationwide.
Figure 3.19. The effect of mean annual precipitation on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and precipitation p<0.001, DF=350, N=351).

The mean SOC pool for all data ranged from 62.3 Mg C ha\(^{-1}\) for MAP of 11 cm yr\(^{-1}\) to 34.9 Mg C ha\(^{-1}\) at 141 cm yr\(^{-1}\). Notably high SOC pool was measured in soils with MAP of 75 cm yr\(^{-1}\) (125.5 Mg C yr\(^{-1}\)). Conversely, low SOC pools are observed in soils receiving MAP of 21 cm yr\(^{-1}\) (47.6 Mg C ha\(^{-1}\)), 39 cm yr\(^{-1}\) (51.8 Mg C ha\(^{-1}\)), 116 cm yr\(^{-1}\) (41.9 Mg C ha\(^{-1}\)), 123 cm yr\(^{-1}\) (46.6 Mg C ha\(^{-1}\)), and 141 cm yr\(^{-1}\) (34.9 Mg C ha\(^{-1}\)) (Figure 3.20).
Figure 3.20. The effect of mean annual precipitation on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by precipitation $p<0.001$, DF=341, N=342, for interactions between sites see table 3.3).
Table 3.3. Interaction of mean soil organic carbon pool by mean annual precipitation at a depth of 0-15 cm (* Indicates significant difference of means at p<0.05).

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Similar to the interaction of MAT on SOC concentration and pool, the effect of MAP on SOC concentration ($R^2=.19$) and SOC pool ($R^2=.18$) was highly variable to 15 cm depth. However, as described previously, high variability was likely due to limited sample size and data availability. Regardless of variability, results support the hypothesis that SOC concentration and pool increase with increase in MAP. However, the decrease in SOC concentration and pool following additional increase in MAP above the threshold contradicts the hypothesis.
Increase in SOC concentration and pool with high MAP have been observed in drylands of the southwest U.S. (Shen et al., 2008). In these regions, plant growth is limited by low water availability. Thus, increases in MAP of these soils results in increased plant growth and subsequent SOC sequestration through contributions of added biomass. This too is likely the cause of the initial increase in SOC concentration and pool in the home lawn turfgrasses below the threshold MAP. Increase in grass available water in these dry soils increase productivity. Increased grass growth and root biomass are in turn contributing to the sequestration of SOC with increased MAP.

Any further increase in MAP beyond the threshold, however, decreased the home lawn SOC concentration and pool. These results are similar to those reported by Derner and Schuman (2007) who observed a similar precipitation threshold for SOC sequestration at 60 cm yr\(^{-1}\) in grasslands to 20 cm depth. This decrease in SOC concentration and pool with additional MAP may be explained through increases in soil microbial biomass. Additional MAP above the threshold was likely contributing to increased soil microbial biomass which in turn was increasing the rate of SOC decomposition. Additionally, increased MAP may increase nutrient cycling in the labile OM, accelerating decomposition of the previously stable SOC pool (Zak et al., 1994).

**Interaction of Temperature and Precipitation on Soil C Concentration and Pool:**

The effects of MAT and MAP individually on SOC concentration in turfgrass soils were discussed in the previous section. However, SOC was also influenced by the interaction among these variables. There may indeed be an optimal combination of temperature and precipitation to attain a high SOC concentration and pool.
It is also possible that MAT and MAP are directly correlated with one another, because increase in MAP may decrease MAP, and vice versa. Such a trend may have a significant impact on both the SOC concentration and pool in turfgrass systems. However, data show no direct correlation between MAT and MAP for the sites chosen in this study (p=0.323; Figure 3.21).

Figure 3.21. The interaction of mean annual temperature and mean annual precipitation for 16 sites utilized in the present study (ANOVA for interaction of temperature and precipitation p=0.323, N=16).
Any interactive effect of MAT and MAP on SOC concentration in 0-2.5 cm depth is depicted in Fig. 3.22. The highest SOC concentrations occurred in sites with low MAT and moderate MAP. Optimal conditions for SOC sequestration were in sites with MAT of 5-10ºC and MAP of 60-90 cm (Figure 3.22).

The relationship of HDD and MAP in the 0-2.5 cm layer is shown in Figure 3.23. The highest SOC concentrations were observed in sites with high HDD and moderate MAP. Optimal climatic conditions for SOC sequestration were in sites with 60-90 cm of MAP and HDD of 3800-4800 HDD per year (Figure 3.23).

The graphic relationship between CDD and MAP in the 0-2.5 cm depth is shown in Figure 3.24. The highest SOC concentrations were measured in sites with low CDD and moderate MAP. Optimal climatic conditions for SOC sequestration at this depth include 60-90 cm of MAP and 200-600 CDD per year (Figure 3.24).
Figure 3.22. Surface graphs illustrating soil organic carbon concentration at a depth of 0-2.5 cm over a range of mean annual temperatures and mean annual precipitations.
Figure 3.23. Surface graphs illustrating soil organic carbon concentration at a depth of 0-2.5 cm over a range of mean annual heating degree days and mean annual precipitations.
Figure 3.24. Surface graphs illustrating soil organic carbon concentration at a depth of 0-2.5 cm over a range of mean annual cooling degree days and mean annual precipitations.
The graphic relationship between MAT, CDD, HDD, and MAP at 2.5-5 cm, 5-10 cm and 10-15 cm depths were similar to the relationships at 0-2.5 cm depth (Appendix C). At all three depths, the highest SOC concentrations occurred in sites with low MAT and moderate MAP. Additionally, optimal conditions for SOC sequestration at 2.5-5 cm, 5-10 cm and 10-15 cm depths were in sites with MAT of 5-10ºC, 5-10ºC and 6-8ºC, respectively and MAP of 60-90 cm, 60-100 cm and 65-85 cm, respectively. Furthermore, at all three depths, the highest SOC concentrations were observed in sites with high HDD and moderate MAP. Optimal conditions for SOC sequestration at 2.5-5 cm, 5-10 cm and 10-15 cm depths were in sites with 60-100cm, 60-100cm, and 65-85cm of MAP, respectively and HDD of 3600-5200, 3500-5200, and 4000-5000 per year, respectively. Finally, at all three depths, the highest SOC concentrations were observed in sites with low CDD and moderate MAP. Optimal conditions for SOC sequestration at 2.5-5 cm, 5-10 cm and 10-15 cm depths were in sites with 60-90cm, 60-100cm, and 65-80cm of MAP, respectively and CDD of 100-700, 0-700, and 250-500 per year, respectively.

Trends for the entire soil profile (0-15 cm) were similar to those for all four separate depths. Interactive effect of MAT and MAP on SOC concentration in 0-15 cm depth is depicted in Fig. 3.25. The highest SOC concentrations occurred in sites with low MAT and moderate MAP. Optimal conditions for SOC sequestration were in sites with MAP of 6-9ºC and MAP of 60-90 cm (Figure 3.25).

The relationship of HDD and MAP in the 0-15 cm depth is shown in Fig. 3.26. The highest SOC concentrations were observed in sites with high HDD and moderate MAP. Optimal climatic conditions for SOC sequestration were in sites with 60-90 cm of MAP and HDD of 3800-4800 HDD per year (Figure 3.26).
The graphic relationship between CDD and MAP for 0-15 cm depth is shown in Fig. 3.27. The highest SOC concentrations were observed in sites with low CDD and moderate MAP. Optimal climatic conditions for SOC sequestration at this depth included 65-85 cm of MAP and 250-550 CDD per year (Figure 3.27).
Figure 3.25. Surface graphs illustrating soil organic carbon concentration at a depth of 0-15 cm over a range of mean annual temperatures and mean annual precipitations.
Figure 3.26. Surface graphs illustrating soil organic carbon concentration at a depth of 0-15 cm over a range of mean annual heating degree days and mean annual precipitations.
Figure 3.27. Surface graphs illustrating soil organic carbon concentration at a depth of 0-15 cm over a range of mean annual cooling degree days and mean annual precipitations.
In addition to the SOC concentration, the SOC pool was also effected by variations in MAT and MAP. Trends for the entire soil profile (0-15 cm) were similar to those for SOC concentration. At 0-15 cm depth, the maximum SOC pool occurred where MAP was moderate (60-90 cm yr\(^{-1}\)) and MAT was low (4-8°C). The interactive effect of MAT and MAP on SOC pool in 0-15 cm depth is depicted in Fig. 3.28. The SOC pool decreased with increase in MAT and as MAP decreased or increased above or below the optimal MAP (60-90 cm yr\(^{-1}\)).

The relationship of HDD and MAP on the SOC pool in the 0-15 cm depth is shown in Fig. 3.29. At 0-15 cm depth, the maximum SOC pool occurred where MAP was moderate (60-90 cm yr\(^{-1}\)) and HDD was high (3800-5000 degree days). The interactive effect of HDD and MAP on the SOC pool in 0-15 cm depth is depicted in Fig. 3.29. SOC pool decreased with decrease in HDD and as MAP decreased or increased above or below the optimal MAP (60-90 cm yr\(^{-1}\)).

The graphic relationship between CDD and MAP in the 0-15 cm depth is shown in Fig. 3.30. The highest SOC concentrations were observed in sites with low CDD (100-700 degree days) and moderate MAP 60-90 cm yr\(^{-1}\). The interactive effect of CDD and MAP on the SOC pool in 0-15 cm depth is depicted in Fig. 3.29. The SOC pool decreased with increase in CDD and as MAP decreased or increased above or below the optimal MAP (60-90 cm yr\(^{-1}\)).
Figure 3.28. Surface graphs illustrating soil organic carbon pool to a depth of 15 cm over a range of mean annual temperatures and mean annual precipitations.
Figure 3.29. Surface graphs illustrating soil organic carbon pool to a depth of 15 cm over a range of mean annual heating degree days and mean annual precipitations.
Figure 3.30. Surface graphs illustrating soil organic carbon pool to a depth of 15 cm over a range of mean annual cooling degree days and mean annual precipitations.
Soil Nitrogen and Soil Carbon Concentration and Pool:

In conjunction with climatic factors, numerous soil properties significantly affected the SOC concentration and pool. In various ecosystems, soil nitrogen (N) concentration was positively correlated with SOC concentration.

The SOC concentration following initial sequestration in home lawn turfgrass systems indicated significantly different concentrations with varied N concentrations. Linear regressions of SOC concentration over a range of soil N concentrations for four separate depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated an increase in SOC concentration with an increase in soil N concentration (p<0.001; Figure 3.31). Rates of SOC change with increase in N concentration were similar for all four depths, ranging from 0.71% per 0.1% increase in N concentration at 10-15 cm depth to 1.12% at 0-2.5 cm depth.
Figure 3.31. The effect of soil nitrogen concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and N concentration at a depth of 0-2.5cm: p=0.002; for all other depths p<0.001, DF=340, N=341 for each depth).

Similarly, linear regression analysis of SOC concentration over a range of N concentrations for the entire soil profile (0-15 cm) indicated a significant increase in SOC concentration with increase in N concentration (p<0.001; Figure 3.32). For 0-15 cm depth, SOC concentrations increased 0.99% for each 0.1% increase in soil N concentration. Therefore, each 1% increase in soil N concentration can result in an increase in SOC concentration of 9.93%.
Figure 3.32. The effect of soil nitrogen concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and soil N concentration p<0.001, DF=340, N=341).

The average SOC concentration for all data ranged from 1.3% for N concentrations of 0-0.10% to 7.0% at 0.51-0.60% (Figure 3.33). Mean SOC concentrations were highly correlated with soil N concentrations ($R^2=.94$), illustrating the importance of soil N concentration in SOC sequestration.
Figure 3.33. The effect of soil nitrogen concentration on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by soil N concentration p<0.001, DF=340, N=341, means with different letters are significantly different at p<0.05).

The SOC pool to a 15 cm depth also increased with increase in soil N concentration (p<0.001; Figure 3.34). For the 0-15 cm depth, the SOC pool increased 23.3 Mg C ha$^{-1}$ for each 0.1% increase in soil N concentration. Therefore, each 1% increase in soil N concentration can result in an increase in SOC pool by 232.9 Mg C ha$^{-1}$.
Figure 3.34. The effect of soil nitrogen concentration on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and soil N concentration $p<0.001$, DF=340, N=341).

The average SOC pool for all data ranged from 30.3 Mg C ha$^{-1}$ for N concentrations of 0-0.10% to 6152.9 Mg C ha$^{-1}$ at 0.51-0.60% (Figure 3.35). Similar to the interaction between mean SOC and N concentrations, mean SOC pools were strongly correlated with soil N concentrations ($R^2=.94$), indicating the importance of soil N concentration in SOC pool.
Figure 3.35. The effect of soil nitrogen concentration on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by soil N concentration $p<0.001$, DF=340, N=341, means with different letters are significantly different at $p<0.05$).

Both SOC and N concentrations were highly correlated. A strong increase in SOC concentration was observed with increase in soil N concentration, an interaction that may be due to a variety of factors. First, increased concentrations of soil N can decrease litter decomposition and soil respiration (Franklin et al., 2003). Additionally, increased soil N concentrations may directly slow SOC decomposition, increasing its MRT (Hyvonen et al., 2008; Magnani et al., 2007). Furthermore, Hopkins et al. (2011) reported that increases in the soil N concentration in grasslands subsequently increased
rates of C mineralization. Finally, greater concentrations of soil N may improve grass growth as well as increase both aboveground and belowground biomass. Increases in biomass may accentuate mineralization and increase storage of SOC. It is likely that a variety of these mechanisms are taking place in home lawn turfgrasses with high concentrations of N. Due to this fact, N fertilization may be a significant factor in determining the SOC sink capacity of U.S. home lawns.

**Soil Texture and Soil Organic Carbon Concentration and Pool:**

Soil texture may also affect the capability of soils to sequester SOC (Tron et al., 1997; Burke et al., 1989). However, Percival et al. (2000) have reported contradictory results, indicating no effect of texture on SOC concentration in grasslands. Regression analyses of U.S. home lawn data for four depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated that soil clay content is not significantly correlated with SOC concentration (p>0.05; Figure 3.36).
Figure 3.36. The effect of soil clay concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and clay content at a depth of 0-2.5 cm p=0.817; at a depth of 2.5-5 cm p=0.07; at a depth of 5.0-10 cm p=0.164; at a depth of 10-15 cm p=0.396; DF=353, N=354 for each depth).

Similarly, regression analysis of clay content on the entire soil profile (0-15 cm) was also insignificant (p=0.516; Figure 3.37). In addition, the data were highly variable (R²=.004).
Figure 3.37. The effect of soil clay concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and soil clay content p=0.516, DF=341, N=342).

The mean SOC concentration following initial sequestration ranged from 2.7% for clay contents < 10% to 2.3% at 41-50%. However, no significant differences in mean SOC concentration were observed over a range of clay contents (p=0.504; Figure 3.38).
Figure 3.38. The effect of soil clay concentration on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by clay content \( p=0.504 \), \( \text{DF}=341 \), \( N=342 \), means with different letters are significantly different at \( p<0.05 \)).

Similarly, regression analysis of clay content on the SOC pool over the entire soil profile (0-15 cm) was insignificant (\( p=0.143 \); Figure 3.39), because of the high variability (\( R^2=0.01 \)).
Figure 3.39. The effect of soil clay concentration on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and soil clay content p=0.143, DF=341, N=342).

Finally, the mean SOC pool ranged from 60.5 Mg C ha\(^{-1}\) for clay contents < 10% to 49.5 Mg C ha\(^{-1}\) at 41-50%. However, as in the other analyses, the data showed no significant differences in mean SOC pool over the range of clay contents (p=0.483; Figure 3.40).
Figure 3.40. The effect of soil clay concentration on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by clay content $p<0.273$, DF=341, N=342, means with different letters are significantly different at $p<0.05$).

Regression analyses of soil silt concentration on SOC concentration for four depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated variable interactions by depth. Regressions for 0-10 cm depth showed no correlation between soil silt content and SOC concentration ($p<0.05$; Figure 3.41). However, regression analysis for 10-15 cm depth indicated an increase in SOC concentration with an increase in soil silt concentration ($p=0.005$). Data may indicate an increase in textural importance on SOC with an increase
in depth. However, variability remained high for all depths including the 10-15 cm depth ($R^2=0.03$).

![Graphs showing the relationship between soil silt concentration and organic carbon concentration at different depths.](image)

Figure 3.41. The effect of soil silt concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and silt content at a depth of 0-2.5 cm $p=0.553$; at a depth of 2.5-5 cm $p=0.875$; at a depth of 5-10 cm $p=0.227$; at a depth of 10-15 cm $p=0.005$; DF=353, N=354 for each depth).

While the 10-15 cm depth indicated an increase in SOC concentration with an increase in soil silt concentration, regression analysis of SOC concentration and soil silt
content on the entire soil profile (0-15 cm) indicated no significance (p=0.132; Figure 3.42) and a high variability ($R^2 = 0.01$).

![Figure 3.42](image)

**Figure 3.42.** The effect of soil silt concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and soil silt content $p=0.132$, DF=341, N=342).

The mean SOC concentration following initial sequestration for all sites ranged from 2.2% for silt contents < 10% to 3.0% at 41-50% (Figure 3.43). A trend for increase in soil silt concentration leading to increase in mean SOC concentration ($p<0.001$) was indicated. However, significant differences in means were observed between silt
contents <10% and 11-20% as well as 11-20% and 21-30%. Additionally, significantly different means increased and then decreased indicating that the high variability $(R^2=0.27)$ may reduce confidence in the interaction.

Figure 3.43. The effect of soil silt concentration on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by silt content $p<0.001$, $DF=305$, $N=342$ for each silt content, means with different letters are significantly different at $p<0.05$).

The effect of silt concentration on the SOC pool at 0-15 cm depth was also
insignificant (p=0.354; Figure 3.44). Again, high variability ($R^2=0.006$) also existed between all data over the range of silt concentrations.

![Figure 3.44](image-url)

**Figure 3.44.** The effect of soil silt concentration on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and soil silt content $p=0.354$, DF=341, N=342).

Finally, as measured for the interaction of silt concentrations on the mean SOC concentration in home lawns, mean SOC pool following initial sequestration indicated a positive correlation ($p<0.001$) over a range of silt contents. However, high variability ($R^2=0.19$) and lack of significant differences between individual means limit confidence.
in the interaction. Mean SOC pools following initial sequestration ranged from 47.9 Mg C ha$^{-1}$ at silt concentrations of < 10% to 65.2 Mg C yr$^{-1}$ at 41-50% (Figure 3.45).

![Figure 3.45](image_url)

Figure 3.45. The effect of soil silt concentration on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by silt content p=0.001, DF=305, N=342 for each silt content, means with different letters are significantly different at p<0.05).

While regression analysis indicated no significant correlation at 0-15 cm depth between soil silt and SOC concentrations, combined fine texture concentration (clay + silt) may influence SOC in soils. Regression analyses showed no significant difference in
SOC concentrations with variable clay + silt concentrations at 0-10 cm depth (p>0.05). However, for 10-15 cm depth, SOC concentration initially increased with increase in soil clay + silt concentration until soils reached a fine particle concentration of around 60%, after which SOC concentrations decreased with increase in fine particle concentration (p=0.019). Significance in regression data increased with increase in depth, indicating that the importance of soil texture on SOC concentration may increase with depth.

Figure 3.46. The effect of soil clay plus silt concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and clay plus silt content at a depth of 0-2.5 cm p=0.595; at a depth of 2.5-5 cm p=0.255; at a depth of 5-10 cm p=0.113; at a depth of 10-15 cm p=0.019; DF=353, N=354 for each depth).
While soils for 10-15 cm depth indicated an interaction of SOC concentration and fine soil particles, regression analysis for the entire soil profile (0-15 cm) indicated no correlation between clay+silt concentration and SOC concentration in home lawn turfgrasses (p=0.161; Figure 3.47). In addition to low significance, variability among all data remain exceptionally high ($r^2=0.01$).

Figure 3.47. The effect of soil clay plus silt concentration on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and soil clay plus silt content $p=0.161$, DF=341, N=342).
The mean SOC concentration following initial sequestration for all sites ranged from 2.3% for clay + silt concentrations < 20% to 2.7% at 81-100% (Figure 3.48).

While means at fine textural particle contents of < 20% and 21-40% significantly differed at p<0.05, interaction among all means showed no significance (p=0.061) over the entire range of textural concentrations.

Figure 3.48. The effect of soil clay plus silt concentration on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by clay plus silt content p<0.061, DF=341, N=342, means with different letters are significantly different at p<0.05).
Regression analysis of clay+silt concentration on the SOC pool at 0-15 cm depth indicated no interaction (p=0.237; Figure 3.49). Additionally, high variability (R²<0.009) also existed between all data over the range of clay + silt concentrations.

Figure 3.49. The effect of soil clay plus silt concentration on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and soil clay plus silt content p=0.237, DF=341, N=342).

Finally, mean SOC pool following initial sequestration for all sites ranged from 49.6 Mg C ha⁻¹ at clay + silt contents < 20% to 56.4 Mg C yr⁻¹ at 81-100% (Figure 3.50). As has been discussed by the interactions of SOC concentration and clay + silt content,
differences in SOC pool means were significant at p<0.05 for the fine texture soils < 20% and those with 21-40%. This trend indicated that SOC concentration and pool were enhanced by the initial increase in fine texture particles. However, interaction among all means over the range of soil clay + silt concentrations were not statistically significant (p=0.064).

Figure 3.50. The effect of soil clay plus silt concentration on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by clay plus silt content p<0.064, DF=341, N=342, means with different letters are significantly different at p<0.05).
Research indicated that soil texture may have a wide range of impacts on SOC concentration and pool. While Tron et al. (1997) indicates the importance of clay particles on SOC storage, Percival et al. (2000) reports no interaction among the two variables. Still others indicate the importance of both clay and silt contents on the SOC sink capacity (Oades, 1988; Carter, 1996; Hassink, 1997). Analyses from U.S. home lawn data has identified no correlation between soil texture and SOC concentration and pool for 0-15 cm depth. However, for 10-15 cm depth, there occurred a significant difference in SOC concentration and pool over a range of soil silt and fine particle concentrations. This trend could indicate that soil texture is an increasingly important factor in SOC storage with an increase in depth. One confounding factor in this analyses, however, surrounds both the low number and disproportionate distribution of samples. Sample sizes of soils with low clay and clay + silt concentrations were much larger than those with higher clay and clay + silt concentrations. This trend was likely due to the type of soils being analyzed. However, such an unequal distribution may skew results of textural analysis. Greater number of samples corresponding with each soil texture could result in less data variability and stronger correlations.

**Soil Acidity and Soil Organic Carbon Concentration and Pool:**

Soil acidity may significantly alter soil microbial communities as well as SOC decomposition rates. Thus, if soil pH in home lawns across the U.S. varies by region, soil acidity may influence the sequestration of SOC over time. However, regression
analyses for U.S. home lawns for four depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated no correlation between pH and SOC concentration (p>0.05; Figure 3.51).

Figure 3.51. The effect of soil pH on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and pH at a depth of 0-2.5 cm p=0.559; at a depth of 2.5-5 cm p=0.051; at a depth of 5-10 cm p=0.152; at a depth of 10-15 cm p=0.101; DF=353, N=354 for each depth).
Similarly, regression analysis of SOC concentration over a range of pH's for the entire soil profile (0-15 cm) indicated no significant correlation among SOC concentration and pH (p=0.324; Figure 3.52)

Figure 3.52. The effect of soil pH on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and pH p=0.324, DF=341, N=342).

The mean SOC concentrations following initial sequestration for all data collected ranged from 1.7% at pH of 4.5-5.5 to 2.2% above 7.5. No significant differences were observed in mean SOC concentrations across pH ranges (p=0.08; Figure 3.53).
Figure 3.53. The effect of soil pH on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey’s post test for individual interactions, for all interactions of mean SOC concentration by pH $p=0.08$, DF=353, N=354, means with different letters are significantly different at $p<0.05$).

Similarly, regression analysis of SOC pool over a range of pH's for the entire soil profile (0-15 cm) indicated no significant correlation among SOC pool and pH ($p=0.410$; Figure 3.54).
Figure 3.54. The effect of soil pH on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and pH $p=0.410$, DF=341, N=342).

Finally, mean SOC pool following initial sequestration for all data collected ranged from 25.3 Mg C ha$^{-1}$ in soils with pH 4.5-5.5 to 30.8 Mg C ha$^{-1}$ above 7.5. However, differences between overall mean SOC pools to 15 cm depth were not statistically significant ($p=0.129$; Figure 3.55).
Figure 3.55. The effect of soil pH on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by pH p=0.129, DF=341, N=342, means with different letters are significantly different at p<0.05).

Regression analyses of U.S. home lawn data indicated no significant effect of soil acidity on SOC concentrations or SOC pools across regions. While acidic soils can be correlated with decreased litter and SOC decomposition (Kok and Vandervelde, 1991; Griffith et al., 1995; Spiegelberger et al., 2006) they may also limit plant productivity negating the possible SOC concentration benefits of slower decomposition. Additionally, for pH to strongly influence SOC concentration, it is possible that soils must be highly
acidic (pH<4.5). However, none of the home lawn soils analyzed contain soils with a pH < 4.5.

**Bulk Density and Soil Organic Carbon Concentration and Pool:**

Soil $\rho_b$ may be a critical physical property, often interacting with numerous soil processes including SOC sequestration. Regression analyses on U.S. home lawns for four depths (0-2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm) indicated soil $\rho_b$ is correlated with significant changes in SOC concentration (p<0.05; Figure 3.56). Results of regressions for all four depths indicated an increase in SOC concentration with increase in $\rho_b$ until soils reach a $\rho_b$ of 1.4-1.45 Mg m$^{-3}$. Following this optimal density, SOC concentrations decreased with continued increase in soil $\rho_b$. 
Figure 3.56. The effect of soil bulk density on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration at four separate depths (ANOVA for interaction of SOC concentration and bulk density at a depth of 0-2.5 cm \( p=0.006 \); at a depth of 2.5-5 cm \( p=0.005 \); at a depth of 5-10 cm \( p=0.045 \); at a depth of 10-15 cm \( p=0.018 \), DF=341, N=342 for each depth).

Similarly, regression analysis of SOC concentration over a range of \( \rho_b \) for the entire soil profile (0-15 cm) indicated a nonlinear correlation (\( p<0.001 \); Figure 3.57). As was measured for each depth separately, SOC concentration in soils for 0-15 cm depth increased with increase in \( \rho_b \) to 1.4-1.45 Mg m\(^{-3}\). Additional compaction beyond this threshold, however, was accompanied by decrease in SOC concentrations. Results
indicated optimal SOC concentrations at $\rho_b$ of 1.4-1.5 Mg m$^{-3}$. In order to maximize the SOC sequestration potential of U.S. home lawns, management steps should be taken to ensure $\rho_b$ remain in this range.

![Graph showing the effect of soil bulk density on soil organic carbon concentration in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC concentration and bulk density p<0.001, DF=341, N=342).](image)

The mean SOC concentrations following initial sequestration for all data collected ranged from 2.0% at $\rho_b$ of 1.15-1.25 Mg m$^{-3}$ to 2.4% at 1.55-1.65 Mg m$^{-3}$. Differences in means over a range of $\rho_b$ were significant for all data (p=0.001; Figure 3.58). Notably
high mean SOC concentrations were observed in soils with $\rho_b$ of 1.45-1.55 Mg m$^{-3}$ (3.0%). In contrast, notably low mean SOC concentrations were observed at $\rho_b$ of 1.15-1.25 Mg m$^{-3}$ (2.0%) and 1.55-1.65 Mg m$^{-3}$ (2.4%).

![Figure 3.58](image)

Figure 3.58. The effect of soil bulk density on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by bulk density $p=0.001$, DF=341, N=342, means with different letters are significantly different at $p<0.05$).

As has been discussed for interaction of $\rho_b$ and SOC concentration, regression analysis of SOC pool over a range of $\rho_b$ for the entire soil profile (0-15 cm) indicated a
nonlinear correlation (p<0.001; Figure 3.59). Increase in SOC pool in soils for 0-15 cm depth was observed with increase in $\rho_b$ to 1.45-1.5 Mg m$^{-3}$. Additional compaction beyond this threshold, however, was accompanied by decrease in SOC pool. Results indicated an optimal SOC pool at $\rho_b$ of 1.45-1.5 Mg m$^{-3}$.

![Figure 3.59](image)

Figure 3.59. The effect of soil bulk density on soil organic carbon pool in home lawn turfgrasses following initial SOC sequestration to a depth of 15 cm (ANOVA for interaction of SOC pool and bulk $p<0.001$, DF=341, N=342).

Finally, the mean SOC pool following initial sequestration for all data collected ranged from 41.9 Mg C ha$^{-1}$ at $\rho_b$ of 1.15-1.25 Mg m$^{-3}$ to 56.5 Mg C ha$^{-1}$ at 1.55-1.65 Mg
m$^3$. Differences in means over the range of $\rho_b$ were significant for all data ($p<0.001$; Figure 3.60). Notably high mean SOC pools were observed in soils with $\rho_b$ of 1.45-1.55 Mg m$^3$ (68.1 Mg C ha$^{-1}$). In contrast, notably low mean SOC concentrations were observed at $\rho_b$ of 1.15-1.25 Mg m$^3$ (41.9 Mg C ha$^{-1}$) and 1.55-1.65 Mg m$^3$ (56.5 Mg C ha$^{-1}$).

![Figure 3.60](image.png)

Figure 3.60. The effect of soil bulk density on the mean soil organic carbon pool for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC pool by bulk density $p<0.001$, DF=341, N=342, means with different letters are significantly different at $p<0.05$).
Results of regression analyses indicated a nonlinear correlation between SOC concentration and $\rho_b$ in U.S. home lawns. At low soil compaction, increase in density increased both SOC concentration and pool. This is likely due to increases in soil mass for SOC sequestration. Additionally, decrease in compaction can improve turfgrass production and subsequently increase the SOC pool (Golubiewski, 2006). However, as soils are compacted their capacity to sequester SOC slows and then decreases. Highly compacted soils can limit fresh OM inputs which in turn may decrease SOC storage (Brevik et al., 2002). Analysis of results indicated this shift from positive to negative interaction among compaction, and SOC sequestration occurs at $\rho_b$ of 1.4-1.5 Mg m$^{-3}$. Thus, in order to increase the SOC sequestration potential of home lawn turfgrasses, low C-intensive management practices should be utilized to maintain these optimal $\rho_b$.

**Turf Species and Soil Organic Carbon Concentration and Pool:**

Across the nation, a variety of turfgrass species are established based on their growing capabilities throughout certain regions (Table 3.3). However, often non-optimal species are planted to obtain a desired aesthetic quality. The SOC concentration in U.S. home lawns over a range of grass species was analyzed to determine any interaction of species on SOC concentration and pool. At 0-15 cm depth, mean SOC concentration following initial sequestration varied from 2.0% in Zoysiagrass dominated soils to 3.3% in Kentucky Bluegrass (*Poa pratensis*) soils. A significant interaction among all grass species was observed ($p<0.001$; Figure 3.61), with Kentucky Bluegrass established soils having SOC concentrations significantly higher than those planted to any other species.
<table>
<thead>
<tr>
<th>Turfgrass Species</th>
<th>Grass Seasonal Type</th>
<th>Optimal Soil Texture</th>
<th>Light Tolerance</th>
<th>Drought Tolerance</th>
<th>Overall Management Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bent</td>
<td>Cool</td>
<td>Fine</td>
<td>Partial Shade</td>
<td>Very Low</td>
<td>Very High</td>
</tr>
<tr>
<td>Bermuda</td>
<td>Warm</td>
<td>Wide Range</td>
<td>Full Sun</td>
<td>Very High</td>
<td>Low</td>
</tr>
<tr>
<td>Buffalo</td>
<td>Warm</td>
<td>Med-Fine</td>
<td>Full Sun</td>
<td>High</td>
<td>Very Low</td>
</tr>
<tr>
<td>KY Blue</td>
<td>Cool</td>
<td>Sand-Silt Loams</td>
<td>Full Sun 3-4hrs/day</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>St Augustine</td>
<td>Warm</td>
<td>Sandy</td>
<td>Sun or Shade</td>
<td>Very High</td>
<td>Low</td>
</tr>
<tr>
<td>Zoysia</td>
<td>Warm</td>
<td>Wide Range</td>
<td>Sun or Shade</td>
<td>Very High</td>
<td>Medium</td>
</tr>
</tbody>
</table>

* Adapted from Fermanian and Voight (2011)

Table 3.3. Turfgrass characteristics for all species sampled in this study.
Figure 3.61. The effect of grass species on the mean soil organic carbon concentration for home lawn turfgrasses in 16 sites following initial SOC sequestration to a depth of 15 cm. (One-way ANOVA with Tukey's post test for individual interactions, for all interactions of mean SOC concentration by grass species p<0.001, DF=341, N=21-129 for each species, means with different letters are significantly different at p<0.05).

Additionally, the SOC pool in U.S. home lawns over a range of grass species was analyzed to determine any interaction of species on the SOC pool. At 0-15 cm depth, mean SOC pool following initial sequestration ranged from 42.9 Mg C ha\(^{-1}\) in Zoysiagrass \((Zoysia matrella)\) dominated soils to 70.9 Mg C ha\(^{-1}\) in Kentucky Bluegrass soils. A significant interaction among all grass species was observed \((p<0.001; \text{Figure 3.62})\), with Kentucky Bluegrass established soils having SOC pools significantly higher than those planted to any other species.
While mean SOC concentration and pool data following initial sequestration indicated differences among all species, significantly higher SOC concentrations and pool were observed in soils with Kentucky Bluegrass established turfs only. Notably high SOC pool and concentrations in Kentucky Bluegrass established soils may be due to desirable species properties which enhance SOC sequestration. For instance, Kentucky Bluegrass productivity may be higher than those of other species, significantly increasing
organic inputs. Additionally, these grasses may be drought tolerant or less prone to fungal infections than other species studied. However, high concentrations of mean SOC may be attributed to disproportionate growth across climatic regions. Some species, including Kentucky Bluegrass, are grown in a variety of climates while others are limited to one. For instance, Buffalograss (*Buchloe palustris*) is grown only within the Wichita, KS site and thus all data on Buffalograss were acquired from soils under a similar climate regime. Due to this fact, climatic interactions may be observed as species interactions. Additionally, Kentucky Bluegrass was grown in Minneapolis, MN, which has significantly higher SOC concentrations than any other location. These high SOC pools have previously been attributed to the optimal climate for SOC sequestration in Minneapolis. Thus, the notably high SOC concentration data in Minneapolis may incorrectly skew the species data. Analysis of data as a whole indicated variations in SOC concentrations and pool among grass species were most likely due to changes in climate and soil properties as discussed above.

**Interaction of Climate and Soil Characteristics on Soil Organic Carbon Concentration and Pool:**

This chapter has focused on the individual interactions among climate and soil properties and SOC concentration in home lawn turfgrasses. As previously indicated, climatic factors of MAT and MAP along with the soil properties of \( \rho_b \) and N concentration can influence the SOC concentration and pool in turfgrass soils. While these interactions provide valuable information into the SOC sequestration potential of
home lawns, relationships among variables may significantly contribute to SOC sequestration.

Utilizing a best subsets regression analysis, interaction among all significant variables (MAT/HDD/CDD, MAP, N concentration, ρ_b) on the SOC concentration for 0-15 cm depth was analyzed. Analyses of regressions containing all significant variables can be viewed in Table 3.4.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mallows Cp</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC concentration by T, T², P, P², N, ρ_b, ρ_b²</td>
<td>8.0*</td>
<td>0.64</td>
</tr>
<tr>
<td>SOC Concentration by CDD, CDD², P, P², N, ρ_b, ρ_b²</td>
<td>8.0*</td>
<td>0.64</td>
</tr>
<tr>
<td>SOC Concentration by HDD, HDD², P, P², N, ρ_b, ρ_b²</td>
<td>8.0*</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 3.4. Best subset regression analysis for interaction of climatic and soil characteristics on soil organic carbon concentration (T=mean annual temperature, HDD=mean annual heating degree days, CDD=mean annual cooling degree days, P=mean annual precipitation, N= nitrogen concentration, ρ_b=bulk density; * indicates Cp ≤ p+1).

Utilizing the results of multiple regression analyses, model regressions were developed for the determination of SOC concentration by climatic variables and soil properties (Table 3.5). Each model includes the significant variables as determined by the best subsets regressions.
Multiple Regression Analysis

0-15 cm

<table>
<thead>
<tr>
<th>Variables</th>
<th>Regression Model Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T, T^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>$[SOC] = -15.3 - 0.06T + 0.002T^2 + 0.01P - 0.00008P^2 + \frac{8.96N}{(100)} + \frac{7.81\rho_b}{(100)}$</td>
<td>0.64</td>
</tr>
<tr>
<td>$HDD, HDD^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>$[SOC] = -16.1 - 0.000008HDD + 1 \times 10^{-7}HDD^2 + 0.01P - \frac{0.0008P^2}{(100)} + \frac{8.93N}{(100)} - \frac{7.97\rho_b}{(100)}$</td>
<td>0.64</td>
</tr>
<tr>
<td>$CDD, CDD^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>$[SOC] = -16.1 - 0.0002CDD + 1 \times 10^{-7}CDD^2 + 0.0P - \frac{0.001P^2}{(100)} + \frac{9.15N}{(100)} - \frac{8.0\rho_b}{(100)}$</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 3.5. Multiple regression analysis for interaction of climatic and soil characteristics on total soil organic carbon (T=mean annual temperature, HDD=mean annual heating degree days, CDD=mean annual cooling degree days, P=mean annual precipitation, N=nitrogen concentration, $\rho_b$=bulk density).

Similarly, interaction of all significant variables (MAT/HDD/CDD, MAP, N concentration, $\rho_b$) on the SOC pool for 0-15 cm depth were analyzed. Analyses of regressions containing all significant variables can be viewed in Table 3.6.

Best Subsets Regression

0-15 cm

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mallows Cp</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC Pool by $T, T^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>8.0*</td>
<td>0.71</td>
</tr>
<tr>
<td>SOC Pool by $CDD, CDD^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>8.0*</td>
<td>0.71</td>
</tr>
<tr>
<td>SOC Pool by $HDD, HDD^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>8.0*</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Table 3.6. Best subset regression analysis for interaction of climatic and soil characteristics on soil organic carbon pool (T=mean annual temperature, HDD=mean annual heating degree days, CDD=mean annual cooling degree days, P=mean annual precipitation, N=nitrogen concentration, $\rho_b$=bulk density; * indicates Cp $\leq$ p+1).
Finally, utilizing the results of multiple regression analyses, model regressions were formed for the determination of SOC pool by climatic variables and soil properties (Table 3.5). Each model includes the significant variables as determined by the best subsets regressions.

### Multiple Regression Analysis

#### 0-15 cm

<table>
<thead>
<tr>
<th>Variables</th>
<th>Regression Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T, T^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>SOC Pool = -213 - 1.4$T + 0.04T^2 + 0.27P - 0.002P^2 + 214N + 281\rho_b - 85.0\rho_b^2$</td>
<td>0.71</td>
</tr>
<tr>
<td>HDD, HDD$^2$, P, P$^2$, N, $\rho_b, \rho_b^2\rho_b^2$</td>
<td>SOC Pool = -233 + 0.0002HDD + 1x10$^{-7}\text{HDD}^2 + 0.26P - 0.002P^2 + 213N + 291\rho_b - 88.6\rho_b^2$</td>
<td>0.71</td>
</tr>
<tr>
<td>CDD, CDD$^2$, P, P$^2$, N, $\rho_b, \rho_b^2\rho_b^2$</td>
<td>SOC Pool = -228 - 0.005CDD + 2x10$^{-6}\text{CDD}^2 + 0.342P - 0.002P^2 + 218N + 286\rho_b - 87.4\rho_b^2$</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Table 3.7. Multiple regression analysis for interaction of climatic and soil characteristics on total soil organic carbon ($T=$mean annual temperature, $HDD=$mean annual heating degree days, $CDD=$mean annual cooling degree days, $P=$mean annual precipitation, $TN=$nitrogen concentration, $\rho_b=$bulk density).

### 3.4 Conclusions

This chapter was aimed at ascertaining the relationship between key soil properties, climatic variables and the SOC sink capacity of U.S. home lawns. Results indicated a correlation between numerous individual properties and SOC concentration across the United States. Climatic variables of MAT and MAP both significantly altered SOC concentrations and pool. Increases in SOC concentration and pool were observed with decrease in MAT, confirming the hypotheses. It is likely that at lower temperatures,
root and shoot growth were in excess of the SOC decomposition, resulting in SOC sequestration. Additionally, lower temperatures can result in the reduction of soil microbial communities, which in turn minimizes SOC decomposition rates.

In addition to MAT, MAP also significantly affected SOC concentrations and pools nationwide. Results both supported and contradicted hypotheses that SOC concentration and pool increase with increase in MAP. In arid climates, increase in MAP increased SOC pools. However, in climates receiving greater than 60 cm yr\(^{-1}\) of MAP, any additional increase decreased the SOC pool and concentrations. Increased SOC storage in arid climates with increase in MAP was likely due to increased plant growth and subsequently high biomass inputs. In these regions, water availability may significantly limit plant growth. Thus, increased water availability can enhance plant growth, subsequently increasing SOC storage by increasing biomass inputs. However, regions receiving > 60 cm yr\(^{-1}\) of MAP were characterized by high microbial populations, which subsequently increased SOC decomposition rates in soil. Therefore, sites located at low MAT receiving MAP of ~60 cm yr\(^{-1}\) were optimal climates for SOC pool enhancement over time.

In addition to climatic variables, key soil properties were also observed to alter SOC concentrations in home lawns. The SOC concentration and pool significantly increased with increase in N concentration, a trend which may be due to alterations in a number of soil processes. First, higher concentrations of soil N may decrease rates of litter decomposition. Similarly, direct decomposition of SOC is likely to slow with increase in soil N concentrations. Both the decreased decomposition of litter and SOC can increase the SOC sink capacity by increasing its MRT. Furthermore, increased N
concentrations may directly increase rates of C mineralization while simultaneously improving both the aboveground and belowground biomass growth. Thus, enhancement of soil N concentration is likely to result in increased SOC storage due to one or more of these soil interactions. This is especially relevant for turfgrass systems which often receive artificial N inputs through fertilizer use. These results support the conclusion that proper use of chemical N may increase SOC concentrations and pools in home lawns.

In addition to N enrichment, $\rho_b$ significantly alters SOC concentrations in home lawns. Much like the interaction between SOC and MAP, increases in $\rho_b$ result in higher SOC concentrations. However, once soils became compacted beyond 1.4-1.5 Mg m$^{-3}$, increase in $\rho_b$ resulted in a decrease in SOC concentration and pool. Increase in SOC concentration with increase in $\rho_b$ at low compaction is likely due to the increase in soil mass for SOC sequestration. Additionally, low compaction can improve turfgrass growth as rooting potential is increased in uncompacted soils. However, as $\rho_b$ increases, decreases in SOC concentration are likely due to the limiting of fresh OM inputs, especially at lower depths. Thus, results of $\rho_b$ and SOC concentration analyses indicated that in home lawns, $\rho_b$ should be maintained at 1.4-1.5 Mg m$^{-3}$ in order to obtain optimal compaction for soil C enhancement.

Finally, contrary to our hypotheses that SOC concentration and pool will increase with increase in clay content, no significant change in SOC concentration or pool with variation in texture for 0-15 cm depth was observed. While results are contrary to some current research regarding the importance of fine soil textures on SOC concentration, they were in agreement with research by Percival et al. (2000) who found no interaction between soil texture and SOC concentration in grasslands.
Analyses of home lawn turfgrass data in 16 sites throughout the U.S. indicated the significant influence of a number of climatic and soil properties on SOC concentration. Based upon results discussed above, optimal SOC pools were located in regions with low MAT, moderate MAP, high soil N concentrations, and moderate $\rho_b$. In order to maximize the SOC storage capacity of home lawns, when possible, non C-intensive management practices should be utilized to maintain soils within these conditions.

References


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Chapter 4: Net Carbon Sequestration Potential and Emissions in Home Lawn Turfgrasses of Ohio and the United States

Abstract

Soil analyses were conducted on home lawns across diverse ecoregions to determine the capacity of turfgrass soils to sequester soil organic carbon (C). Establishment of home lawn turfgrasses sequestered soil SOC in 16 sites throughout the U.S.. Due to variations in climate and soil properties, sequestration rates varied among sites from 0.9 Mg C ha\(^{-1}\) yr\(^{-1}\) in Orlando, FL to 5.4 Mg C ha\(^{-1}\) yr\(^{-1}\) in Minneapolis, MN. Potential SOC sink capacity also varied among sites ranging from 20.8 \(\pm\) 1.0 Mg C ha\(^{-1}\) in Portland, ME to 96.3 \(\pm\) 6.0 Mg C ha\(^{-1}\) in Minneapolis, MN. Average sequestration rates and sink capacity were 2.8 \(\pm\) 0.3 Mg C ha\(^{-1}\) yr\(^{-1}\) and 45.8 \(\pm\) 3.5 Mg C ha\(^{-1}\), respectively, for all sites analyzed. Differences in SOC sequestration rate nationwide were attributed to differences in mean annual precipitation (MAP), soil nitrogen (N) concentration, fine soil texture, bulk density (\(\rho_b\)), and pH. The potential SOC sink capacity was determined by mean annual temperature (MAT), MAP, soil N concentration, and \(\rho_b\). Additionally, hidden carbon costs (HCC) due to turfgrass maintenance were estimated to be significant. Mean total emissions for lawns analyzed were 254.3 kg carbon equivalent (Ce) ha\(^{-1}\) yr\(^{-1}\) with major emissions due to mowing fuel combustion (189.7 kg Ce ha\(^{-1}\) yr\(^{-1}\)), and N fertilizer use (63.6 kg Ce ha\(^{-1}\) yr\(^{-1}\)). Considering the potential SOC sink capacity of the turfs as well as maintenance emissions due to HCC, average home lawn sequestration was completely negated by total emissions 184 years post establishment. The potential SOC sink capacity of all home lawns in the State of Ohio and the U.S. were estimated at 17.8 and 496.3 Tg C, respectively. Additionally, the HCC due to maintenance under low management conditions were estimated at 82.6 and 2504.1 Gg Ce yr\(^{-1}\) for Ohio and U.S. lawns, respectively. Under high management conditions, these estimations rise to 284.4 and 7551.4 Gg Ce yr\(^{-1}\) for Ohio and U.S. lawns. This leads to a C-positive system for between 71 and 223 years for Ohio's home lawns and between 66 and 199 years in U.S. home lawns before all SOC sequestered is negated through HCC. More efficient and reduction of C-intensive maintenance practices could increase the overall sequestration longevity of home lawns and improve their benefits to climate change mitigation.

Keywords: Carbon Sequestration Rate, Potential C Sink Capacity, Turfgrass, Home Lawns, Hidden Carbon Costs
4.1 Introduction

As rates of urbanization continue to increase, the area and intensity of turfgrass development is also rapidly expanding. Between 1982 and 1992 alone, the area of U.S. urban soils increased by 25% (Pendall, 1999), due in large part to the high number of golf courses built nationally each year. Globally, there are now over 32,000 golf courses characterized by fertile turfs with production rates of biomass nearly as high as agricultural fields (Falk, 1976). Conversion of natural to agricultural systems has depleted the soil organic carbon (SOC) pools (Davidson and Ackerman, 1993; Gebhart et al., 1994; Buyanovsky and Wagner, 1998; Lal and Bruce, 1999; Murty et al., 2002; Ogle et al., 2003). It is believed that the conversion of agricultural soils to highly fertile and managed turfgrass systems can re-sequester much of the carbon (C) lost through agricultural cultivation. This conversion can increase soil fertility through the application of chemical fertilizers, which have numerous beneficial effects on the SOC pools (Conant et al., 2001). In addition to fertilizer application, two other common turfgrass management practices, the increased deposit of organic matter (OM) and irrigation, also increase SOC pools (Wilson, 1991; Brown, 1994).

Numerous studies show that the reversion of agricultural soils back to native grassland sites sequester SOC over time. Conversion of depleted croplands throughout the U.K., New Zealand, Canada, and the U.S. have the potential to sequester between 0.5 and 1.1 Mg C ha$^{-1}$ yr$^{-1}$ (Tyson et al., 1990; Haynes et al., 1991; Mensah et al., 2003; Gebhart et al., 1994) (Table 4.1). Furthermore, upon conversion to golf course systems, native grasslands and prairie sites sequester an additional 0.2-0.9 Mg C ha$^{-1}$ yr$^{-1}$ (Qian and Follett, 2002; Bandaranayake et al., 2003; Huh et al., 2008) (Table 4.1). The
increased soil fertility accompanying these conversions increases SOC pools, which is a useful climate change mitigation strategy. Similarly, the conversion of cropland to golf course turfgrasses can sequester as much as 3.6 Mg C ha\(^{-1}\) yr\(^{-1}\) in the fairways and 2.5 Mg C ha\(^{-1}\) yr\(^{-1}\) in rough systems (Selhorst and Lal, 2011) (Table 4.1). This accelerated rate of sequestration indicates that conversion of a depleted system to a golf course turfgrass has a high potential to sequester atmospheric carbon dioxide (CO\(_2\)).

<table>
<thead>
<tr>
<th>Source</th>
<th>Initial Land Use</th>
<th>Final Land Use</th>
<th>Soil Organic Carbon Sequestration Rate (Mg C ha(^{-1}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyson et al., 1990</td>
<td>Cropland (UK)</td>
<td>Grassland</td>
<td>0.82</td>
</tr>
<tr>
<td>Haynes et al., 1991</td>
<td>Cropland (NZ)</td>
<td>Grassland</td>
<td>1.11</td>
</tr>
<tr>
<td>Mensah et al., 2003</td>
<td>Cropland (CA, USA)</td>
<td>Grassland</td>
<td>0.86</td>
</tr>
<tr>
<td>Gebhart et al., 1994</td>
<td>Cropland (USA)</td>
<td>Grassland</td>
<td>0.47</td>
</tr>
<tr>
<td>Qian and Follett, 2002</td>
<td>Grasslands (CO, USA)</td>
<td>Golf Course</td>
<td>0.90</td>
</tr>
<tr>
<td>Bandaranayake, 2003</td>
<td>Grasslands (CO, USA)</td>
<td>Golf Course</td>
<td>0.15</td>
</tr>
<tr>
<td>Huh et al., 2008</td>
<td>Grasslands (NZ)</td>
<td>Golf Course</td>
<td>0.69</td>
</tr>
<tr>
<td>Qian et al., 2010</td>
<td>Prairie (NE, USA)</td>
<td>Golf Course</td>
<td>0.32-0.78</td>
</tr>
<tr>
<td>Selhorst, 2011</td>
<td>Cropland (OH, USA)</td>
<td>Golf Course</td>
<td>2.47-3.58</td>
</tr>
</tbody>
</table>

Table 4.1. Soil organic carbon sequestration rate following land use conversion in various sites throughout the world.

While conversion to golf course turfgrass systems can sequester SOC over time, other turf systems may also have a high sequestration potential. Home lawns for instance are also highly fertile systems and can increase SOC pools. As urbanization and human population grow, the addition of housing units throughout the world is needed to
accommodate this growth. In many regions of the world this proliferation of housing units can increase the area of turf growth as homes are surrounded by managed lawns. During the 2000's, the U.S. alone witnessed the construction of over 13.5 million new single family homes (Table 4.2), the majority of which were surrounded by a newly planted lawn. The development of a fertile turf at each of these sites adds to the greenspace area capable of SOC sequestration.

<table>
<thead>
<tr>
<th>State</th>
<th>Number of Housing Units (Millions)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>July 2000</td>
<td>July 2010</td>
</tr>
<tr>
<td>California</td>
<td>12.2</td>
<td>13.4</td>
</tr>
<tr>
<td>Texas</td>
<td>8.2</td>
<td>9.7</td>
</tr>
<tr>
<td>Florida</td>
<td>7.3</td>
<td>8.9</td>
</tr>
<tr>
<td>New York</td>
<td>7.7</td>
<td>8.0</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>5.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Illinois</td>
<td>4.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Ohio</td>
<td>4.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Michigan</td>
<td>4.2</td>
<td>4.5</td>
</tr>
<tr>
<td>North Carolina</td>
<td>3.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Georgia</td>
<td>3.3</td>
<td>4.1</td>
</tr>
<tr>
<td>New Jersey</td>
<td>3.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Virginia</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Washington</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Indiana</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Tennessee</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Mean All U.S. States</strong></td>
<td><strong>2.3</strong></td>
<td><strong>2.5</strong></td>
</tr>
<tr>
<td><strong>Total All U.S. States</strong></td>
<td><strong>116.3</strong></td>
<td><strong>130.0</strong></td>
</tr>
</tbody>
</table>

*Adapted from U.S. Census Bureau (2011b)
Table 4.2 Change in number of housing units over a 10 year period for the top 15 states by number of units.

In addition to sequestering SOC, turfgrasses have numerous other environmental benefits. They can provide erosional control by stabilizing erodible soil. Their absorbent
water carrying capacity can provide high groundwater recharge potential as well as flood control in regions receiving erosive rains. They may also provide fire breaks, noise dissipation, and heat abatement, all while offering recreational area (Beard and Green, 1994).

In spite of the benefits and SOC sink capacity of turfs, there are numerous downsides to the development of urban turfgrass systems. To produce and maintain highly fertile and productive turfs, significant C-intensive inputs are required to ensure the health of these ecosystems. Overall, home lawn maintenance practices produce an energy requirement of around 578 kcal m\(^{-2}\) yr\(^{-1}\) (Falk, 1976). Americans alone spend over $45 billion per year on turfgrass maintenance with an average home owner spending over $200 annually (Beard and Green, 1994; Meyer et al., 2001).

Major maintenance practices consist of fossil fuel driven lawn mowing, the application of fertilizers, pesticides, and herbicides, as well as the use of irrigation (Witteven and Bavier, 2005). These hidden carbon costs (HCC) lead to significant annual C emissions, especially in high management areas such as those required by golf courses. Fuel use for instance is responsible for emitting 0.85 kg of carbon equivalent (Ce) into the atmosphere for every 1 kg of gasoline combusted and 0.94 kg Ce for every 1 kg of diesel fuel combusted (Boustead and Hancock, 1979; Fluck, 1992). With golf courses mowing up to twice daily, this can emit a massive annual flux of C into the atmosphere.

The use of fertilizers, pesticides, and herbicides, also has significant HCC. Depending on the type of formulation, fertilizers can produce between 0.1 and 1.8 kg Ce for each 1 kg of fertilizer applied. Insecticides and fungicides have an even larger impact.
on the net C budget emitting between 1.2 and 12.6 kg Ce for every 1 kg of active ingredient used (Lal, 2004). Over and above the C emissions released by the application of these chemicals, there are also additional negative externalities associated with their use. Surface runoff and leaching of chemicals can lead to groundwater contamination, surface pollution, and the need for additional applications if the applied product was not sufficiently absorbed. The application of nitrogen (N) fertilizers for turf maintenance purposes may lead to leaching losses of as much as 53% (Petrovic, 1990). While this is a serious concern, turf fertilizer nutrient losses are low compared to agronomic row crops (Gross et al., 1990). Regardless, runoff of fertilizers necessitate additional applications and increased emissions. Furthermore, pesticide applications can significantly contaminate both ground and surface waters with ~15% of the pesticide concentrations found in groundwater coming from suburban home lawn systems (Gold and Groffman, 1993).

Another major HCC involves the need for supplemental irrigation. In many regions of the country, turf must be frequently irrigated to ensure proper development and maintenance. Sloggett (1979) predicted that nearly 23% of all farm energy was utilized for pumping irrigation water. This stat may hold true for golf courses or home lawns grown in hot dry climates such as Las Vegas, NV or Phoenix, AZ. Blancomontero et al. (1995) reported that turfgrasses in Albuquerque, NM used as much as 475,000 m$^3$ day$^{-1}$ of water for irrigation alone. Additionally, the installation of irrigation systems causes significant C emissions, with as much as 121 kg Ce ha$^{-1}$ attributed to this process (Batty and Keller, 1980). In addition to the increased C footprint due to irrigation, water use for turf development in regions with an already scarce supply, increases the overall
environmental impact. While many of the maintenance practices are considered vital for the proper development of turf systems, the high HCC can significantly decrease the net SOC sink capacity of the system.

While the development and maintenance of turf systems can have a range of negative environmental impacts, there are strategies to limit these impacts ensuring the benefits of turf development are maximized. There are a number of best management practices (BMP) that can help ensure this maximization. First and foremost, proper application rate of fertilizers and pesticides affects the leaching losses of added chemicals. Application of N fertilizer at rates that match N requirements can ensure minimal runoff and maximum benefit to the turf. Additionally, efficient irrigation use can minimize the leaching of chemicals. Irrigation amounts limiting water movement below the active rooting zone can significantly limit leaching from soils (Morton et al., 1988; Barton and Colmer, 2006). The use of turf buffer areas upon development near open waterways can also limit the runoff of toxic chemicals. Grass buffers maintained at higher mowing heights can reduce pesticide and fertilizer runoff into neighboring streams and rivers (Baird et al., 2000; Barton and Colmer, 2006; Cole et al., 1997). Thus, steps should be taken to maintain these buffer strips, ensuring the protection of nearby waterways. Finally, topdressing with compost can increase the soil water content of turfgrasses, subsequently lowering their overall irrigation requirement. Additionally, compost also improves the turf quality and increases SOC sequestration (Johnson et al., 2009).

Due to the pros and cons discussed above, the SOC sink capacity of turfgrass systems is a complex issue. Thus, SOC pool enhancement must be evaluated in light of
the HCC necessary to establish and sustain highly fertile turfgrass systems. If rates of SOC sequestration remain high in view of maintenance practices, these systems are an important asset in the fight against accelerated climate change (ACC).

The following chapter will serve to determine the potential of Ohio and U.S. home lawns to offset C emissions in lieu of the estimated HCCs due to turfgrass maintenance. Additionally, management recommendations to increase the overall potential C sink capacity of U.S. home lawn turfgrasses will be discussed. It is hypothesized that home lawns will sequester C and aid in atmospheric C enrichment mitigation for approximately 100 years, after which C sequestered through turf establishment will be negated by the HCCs of maintenance.

4.2 MATERIALS AND METHODS

Site description:

Maintenance practices of lawns utilized were similar for mowing frequency, clippings management, and fertilizer application. Irrigation was applied at four sites, however, at these locations turf growth would be impossible without supplemental water management (Table 4.3). See materials and methods in chapter 2 for complete site description.
### Table 4.3. List of maintenance practices for all 16 sampling sites.

<table>
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<tr>
<th>Site</th>
<th>Mowing Frequency</th>
<th>Clippings Treatment</th>
<th>Fertilizer Application</th>
<th>Irrigation Frequency</th>
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**Experimental Design:**

See materials and methods in chapter 3 for complete description of experimental design.

**Soil Sampling and Analyses:**

See materials and methods in chapter 3 for complete description of soil sampling and analyses.

**Soil Carbon Pool Determination:**
See materials and methods in chapter 3 for complete description of soil C pool determination.

**Hidden Carbon Cost Determination:**

In order to determine the total C emissions due to home lawn maintenance in both Ohio and the U.S., estimations were determined from a variety of sources. Estimated area of single family home lawn turfgrass was obtained from the 2009 American Housing Survey (US Census, 2009), while estimates for Ohio were obtained from the 2007 economic impact of Ohio's turfgrass industry report (Kristel et al., 2007).

In order to determine the mean overall gasoline emissions for a single family home lawn mowing for one year the estimation of 9.35 L ha\(^{-1}\) was utilized from Sahu (2008). Mowing season was assumed between April 1 and November 1, with an average of one lawn mowing per week for calculations of low management and two mowings per week for high management estimations. Utilizing data from Lal (2004), the number of kilograms of gasoline was multiplied by 0.85 to determine the kg of Ce emitted each year by gasoline.

In order to determine the C emissions due to fertilizer application the amount of N, phosphorous (P) and potassium (K) fertilizer applied over one year period was estimated. All sites received one fertilizer application per year. Thus, low management estimations assumed one annual application of standard fertilizer (32-0-4) applied at industry recommendations (0.0153 kg m\(^{-2}\)). High management estimations assumed six annual applications of fertilizer at similar rates. The total amount of N, P, and K in kg
applied annually was then multiplied by 1.3, 0.2, and 0.15, respectively, to give the overall kg of Ce per Lal (2004).

Additionally, all sites included in this study received no application of either pesticides or herbicides. As irrigation was used at only a select few locations, its emissions were assumed to be 0. However, this is not the case for turfgrasses located in hot arid climates.

### 4.3 Results and Discussion

**Soil Organic Carbon Sequestration Rate and Sink Capacity by Site:**

Upon development of home lawn turfgrasses, SOC sequestration occurred in all sites analyzed. Rates of SOC sequestration for 0-15 cm depth varied among sites from 0.9 Mg C ha⁻¹ yr⁻¹ in Orlando, FL to 5.4 Mg C ha⁻¹ yr⁻¹ in Minneapolis, MN, equivalent to an average rate of 2.8 ± 0.3 Mg C ha⁻¹ yr⁻¹ (Figure 4.1; Table 4.4; Table 4.6). Similar to differences in SOC concentration and pools, variations in the SOC sequestration rate are probably due to a range of climatic and soil characteristics. These differences are discussed in this chapter.
Figure 4.1. Mean soil organic carbon sequestration rate for 0-15 cm soil depth for 16 sites within the United States (One-way ANOVA with Tukey's post test, for all interactions of mean SOC sequestration rate by location $p<0.001$, DF=344, N=345 Results of individual interactions can be viewed in Table 4.4 to follow).
Table 4.4. Interaction of mean soil organic carbon sequestration rate by location at a depth of 0-15 cm (* Indicates significant difference of means at p<0.05).

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*Indicates significance of p<0.05

Accounting for the SOC sequestration rate and the time for home lawns to initially sequester SOC before stabilizing for decades, the potential SOC sink capacity of home lawn turf soils was determined for each site to 15 cm depth. Potential SOC sink capacity ranged from 20.8 ± 1.0 Mg C ha⁻¹ in Portland, ME, to 96.3 ± 6.0 Mg C ha⁻¹ in Minneapolis, MN, with an average sink capacity of 45.8 ± 3.5 Mg C ha⁻¹ (Figure 4.2; Table 4.5; Table 4.6). In addition to the soils of Minneapolis, MN, a notably high sequestration potential was recorded for the soils of San Francisco, CA (60.9 ± 5.3 Mg ha⁻¹), while below average potentials were observed in the soils of Portland, ME, Atlanta,
GA (29.3 ± 3.3 Mg C ha⁻¹), Seattle, WA (30.7 ± 2.3 Mg C ha⁻¹), Phoenix, AZ (33.0 ± 4.5 Mg C ha⁻¹), and Orlando, FL (34.5 ± 4.6 Mg C ha⁻¹). Differences in rate of SOC sequestration among sites may be attributed to differences in climate and soil factors.

Figure 4.2. Mean potential soil organic carbon sink capacity for 0-15 cm soil depth for 16 sites within the United States (One-way ANOVA with Tukey's post test, for all interactions of mean SOC sequestration rate by location p<0.001, DF=344, N=345 Results of individual interactions can be viewed in Table 4.5 to follow).
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</tbody>
</table>

*Indicates significance of p<0.05
Table 4.5. Interaction of mean potential soil organic carbon sink capacity by location at a depth of 0-15 cm (* Indicates significant difference of means at p<0.05).
<table>
<thead>
<tr>
<th>City</th>
<th>Mean Soil Organic Carbon Sequestration Rate (Mg C ha(^{-1}) yr(^{-1}))</th>
<th>Mean Potential Soil Organic Carbon Sink Capacity (Mg C ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albuquerque, NM</td>
<td>2.3</td>
<td>58.0 ± 4.0</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>2.6</td>
<td>29.3 ± 3.3</td>
</tr>
<tr>
<td>Cheyenne, WY</td>
<td>3.2</td>
<td>43.2 ± 3.3</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>1.9</td>
<td>39.0 ± 1.7</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>1.9</td>
<td>46.3 ± 6.9</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>2.5</td>
<td>50.8 ± 3.6</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>2.9</td>
<td>37.2 ± 2.5</td>
</tr>
<tr>
<td>Las Vegas, NV</td>
<td>3.5</td>
<td>47.2 ± 2.1</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>5.4</td>
<td>96.3 ± 6.0</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>0.9</td>
<td>34.5 ± 4.6</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>2.6</td>
<td>33.0 ± 4.5</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>1.9</td>
<td>20.8 ± 1.0</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>4.9</td>
<td>60.9 ± 5.3</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>2.0</td>
<td>30.7 ± 2.3</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>3.6</td>
<td>48.3 ± 0.5</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>2.3</td>
<td>56.9 ± 3.9</td>
</tr>
</tbody>
</table>

|               | 2.8 ± 0.3                                                 | 45.8 ± 3.5                                                          |
| Mean          |                                                          |                                                                  |
| Range         | 0.9-5.4                                                  | 20.8-96.3                                                           |

Table 4.6. Mean soil organic carbon sequestration rate and potential soil organic carbon sink capacity following initial SOC sequestration for 0-15 cm depth for 16 sites sampled in this study.

The SOC sequestration rate (Figure 4.3) and sink capacity (Figure 4.4) decreased with increase in soil depth (Table 4.7). Surface layers had higher rates and sink capacities per unit area than sub-soil layers. The rate of SOC sequestration was 1.2 Mg C ha\(^{-1}\) yr\(^{-1}\) for 0-5 cm depth compared with 0.74 Mg C ha\(^{-1}\) yr\(^{-1}\) for 10-15 cm depth.

Similarly, the potential SOC sink capacity was 20.4 ± 2.7 Mg C ha\(^{-1}\) for 0-5 cm depth compared with 11.7 ± 1.1 Mg C ha\(^{-1}\) for 10-15 cm depth. Decrease in rate of SOC
sequestration and potential sink capacity with increase in depth were likely a result of increased availability of soil N due to the surface application of chemical fertilizers and high input of biomass C returned through clippings. This interaction may become more pronounced with increased soil compaction, which can limit the ability of surface inputs to reach deeper soil depths.

Figure 4.3. Mean soil organic carbon sequestration rate at four separate depths for 16 sites within the United States (One-way ANOVA with Tukey's post test, for all interactions of mean SOC sequestration rate by depth \( p=0.07 \), DF=3, N=16 for each depth, means with different letters are significantly different at \( p<0.05 \). Error bars = standard error).
Figure 4.4. Mean potential soil organic carbon sink capacity at 4 separate depths for 16 sites within the United States (One-way ANOVA with Tukey's post test, for all interactions of potential SOC sink capacity by depth  \( p=0.07 \), DF = 3, N = 16 for each depth, means with different letters are significant at \( p<0.05 \). Error bars = standard error).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Mean Soil Organic Carbon Sequestration Rate (Mg C ha(^{-1}) yr(^{-1}))</th>
<th>Mean Potential Soil Organic Carbon Sink Capacity (Mg C ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5</td>
<td>0.7 ± 0.1</td>
<td>12.1 ± 1.4</td>
</tr>
<tr>
<td>2.5-5</td>
<td>0.5 ± 0.1</td>
<td>8.3 ± 1.3</td>
</tr>
<tr>
<td>5-10</td>
<td>0.8 ± 0.1</td>
<td>13.7 ± 1.6</td>
</tr>
<tr>
<td>10-15</td>
<td>0.7 ± 0.1</td>
<td>11.7 ± 1.1</td>
</tr>
</tbody>
</table>

Table 4.7. Mean soil organic carbon sequestration rate and potential soil organic carbon sink capacity at 4 depths for 16 sites sampled in this study.
Soil Organic Carbon Sequestration Rate and Sink Capacity by Turfgrass Type:

Golf turfgrass systems have a capacity to sequester SOC at high rates and with a high potential SOC sink capacity. While home lawns are managed less intensively than golf courses, they have high SOC sequestration rates (2.8 Mg C ha\(^{-1}\) yr\(^{-1}\)) at par with rough managed (2.6 Mg C ha\(^{-1}\) yr\(^{-1}\)) golf course turfs. However, golf course fairway managed turfs have higher rates of SOC sequestration at 3.6 Mg C ha\(^{-1}\) yr\(^{-1}\) (Selhorst and Lal, 2011; Figure 4.5; Table 4.8). Significantly higher rates of SOC sequestration in fairway managed soils were expected due to their increased fertilizer application. While copious amounts of fertilizer significantly increase the SOC sequestration rate in fairway soils, their capacity to mitigate climate change depends on their total SOC sink potential. It is possible that while these soils sequester SOC at greater rates, they reach initial sequestration stabilization sooner than those sequestering SOC at slower rates.
Figure 4.5. Mean soil organic carbon sequestration rate in the top 15 cm depth for various land uses within the United States (One-way ANOVA with Tukey’s post test, for all interactions of mean SOC sequestration rate by land use  \( p=0.07 \), DF=2, N=16 for home lawns and N=9 for golf fairway and rough sites. Error bars = standard error).

While sequestration rates of SOC may be similar for rough treated golf course turfs and home lawns, the total potential of SOC sequestration is significantly different for the two systems. Home lawns have a potential SOC sink capacity of 45.8 ± 5.1 Mg C ha\(^{-1}\) to 15 cm depth, while rough managed golf course turfs sequester 61.9 ± 2.4 Mg C ha\(^{-1}\). Additionally, fairway treated turfs have a greater potential by as much as 30.0 ± 1.2 Mg C ha\(^{-1}\) (Figure 4.6; Table 4.8). Differences in potential SOC sink capacity among the three soils were expected due to differences in management intensities. Golf course soils receive intense management, rough soils moderate management, and home lawns...
minimal management. Thus reduced potential SOC sink capacity across fairway, rough, and home lawn soils was expected. Regardless of the potential SOC sink capacity in all three soil types, their net capacity to sequester SOC and mitigate the effects of atmospheric CO₂ enrichment must be viewed in light of HCC. While golf courses have a greater potential to sequester SOC over time, they are much more intensively managed than the average home lawn. Such intensive management through the use of fossil fuel based inputs may negate much of the benefits of increased SOC sequestration.

Figure 4.6. Mean potential soil organic carbon sink capacity in the top 15 cm for various land uses within the United States (One-way ANOVA with Tukey’s post test, for all interactions of mean potential soil organic carbon sink capacity by land use p=0.001, DF=2, N=16 for home lawns and N=9 for golf fairway and rough sites. Error bars = standard error)
Table 4.8. Mean soil organic carbon sequestration rate and potential sink capacity at a depth of 0-15 cm for various land uses.

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Mean Soil Organic Carbon Sequestration Rate (Mg C ha(^{-1}) yr(^{-1}))</th>
<th>Mean Potential Soil Organic Carbon Sink Capacity (Mg C ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home Lawns</td>
<td>2.8 ± 0.3</td>
<td>45.8 ± 5.1</td>
</tr>
<tr>
<td>Golf Rough</td>
<td>2.6 ± 0.1</td>
<td>61.9 ± 2.4</td>
</tr>
<tr>
<td>Golf Fairways</td>
<td>3.6 ± 0.1</td>
<td>73.5 ± 1.2</td>
</tr>
</tbody>
</table>

Effect of Climatic Factors on the Soil Organic Carbon Sequestration Rate and Sink Capacity:

The rate of SOC sequestration to 15 cm depth did not differ significantly (p=0.262) over a range of soils in regions of diverse mean annual temperatures (MAT) (Figure 4.7). Contrary to the results of SOC concentration and pool, rates of SOC sequestration are not linked to MAT (Figure 4.7). While the photosynthetic rate in turfgrasses decreases with increase in MAT (Al-Khatib and Paulson, 1999; Crafts-Brandner and Salvucci, 2000; Xu and Huang, 2000a, 2000b, 2001) the establishment of home lawns may have provided such a vast improvement over previous land uses that SOC sequestration occurred at a high rate over all MAT regimes. It is possible that SOC sequestration rate in all regions may be limited by soil properties, thus minimizing or even negating the effects of climate on SOC sequestration rate.
Figure 4.7. The effect of mean annual temperature on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and temperature p=0.262, DF=344, N=345).

Conversely, regression analysis indicated that the potential SOC sink capacity is negatively correlated (P<0.001) with MAT (Figure, 4.8). At 15 cm depth, the SOC sink capacity decreased by an average of 1.29% for each 1°C rise in MAT. Thus, MAT differences across all sites may account for potential SOC sink differences of as much as 20 Mg C ha⁻¹. While regression analyses indicated no effect of MAT on SOC sequestration rates, the effect of increased MAT on photosynthetic rates in turfgrasses significantly affected the potential SOC sink capacity in home lawns. Additionally, increased MAT is negatively correlated with turf quality and root growth (Pote et al.,
It is probable that this decrease in biomass growth at higher MAT has limited the potential SOC sink capacity of home lawn soils located in high MAT regimes.

Figure 4.8. The effect of mean annual temperature on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of potential SOC carbon sink capacity and temperature p<0.001, DF=344, N=345).

The SOC sequestration rate and sink capacity were also compared for annual number of heating degree days (HDD) and cooling degree days (CDD) to account for yearly temperature range fluctuations. The SOC responded similarly to both CDD and
HDD as to MAT. Regression analysis indicated that number of mean annual CDD had no effect ($P=0.104$) on rate of SOC sequestration (Figure 4.9). Similarly, regression analysis showed that number of mean annual HDD also had no impact ($P=0.564$) on SOC sequestration rate (Figure 4.10). Based on previous results indicating no interaction of MAT on SOC sequestration rate, analyses of number of mean annual CDD and HDD on SOC sequestration rate produced the expected results.

Figure 4.9. The effect of mean number of annual cooling degree days on soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and CDD $p=0.104$, DF=344, N=345).
Figure 4.10. The effect of mean number of annual heating degree days on soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and HDD p=0.564, DF=344, N=345).

In contrast, CDD significantly contributed (P<0.001) to the potential SOC sink capacity in home lawn turfgrass soils (Figure 4.11), illustrating an average decrease of 0.003% for each additional CDD. This trend equates to a 0.001 Mg C ha$^{-1}$ decrease in potential SOC sink capacity for each additional CDD. Similarly, the influence of HDD on potential SOC sink capacity was also significant (p<0.001; Figure 4.12). An increase in 1 HDD in sites increased the potential SOC sink capacity by 0.02% or 0.006 Mg C ha$^{-1}$. Again, based on results of regressions on MAT and potential SOC sink capacity,
analyses of number of mean annual CDD and HDD on SOC sink capacity produced the expected results.

Figure 4.11. The effect of mean number of annual cooling degree days on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of potential SOC sink capacity and CDD p<0.001, DF=344, N=345).
Figure 4.12. The effect of mean number of annual heating degree days on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15.0 cm (ANOVA for interaction of potential SOC sink capacity and HDD p<0.001, DF=344, N=345).

In direct contrast to the effects of MAT on SOC sequestration rate, mean annual precipitation (MAP) had a strong negative correlation (p<0.001) with SOC sequestration rate (Figure 4.13). An increase in MAP by 1 cm yr⁻¹ decreased the rate of SOC sequestration by an average of 0.008 Mg C ha⁻¹ yr⁻¹. This trend may be responsible for a decrease in SOC sequestration rate of over 1.0 Mg C ha⁻¹ yr⁻¹ between the arid and humid region soils analyzed in this study. Such a trend may be attributed to differences in the source of soil N in home lawn turfs. As all lawns in this study received chemical
fertilizers, the surface application of fertilizers may be more effective in regions receiving low MAP. Increase in MAP may increase losses of chemical fertilizers by runoff and leaching of applied N, thus decreasing the effectiveness and use efficiency of fertilizers.

Figure 4.13. The effect of mean annual precipitation on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and precipitation p<0.001, DF=344, N=345).

Similar to the SOC sequestration rate, MAP also had a significant interaction (p<0.001) on the potential SOC sink capacity in home lawn turfgrasses (Figure 4.14). Potential SOC sink capacity followed a polynomial interaction with extreme low and
high MAP leading to a decreased potential SOC sink capacity. Thus, based on regression analysis, an optimal range of MAP for SOC sequestration is 50-70 cm yr\(^{-1}\). Additionally, the impact of MAP on potential SOC sink capacity may be larger for sites with low MAP because lawns sampled in this study at the 4 driest locations all received supplemental irrigation. Without such irrigation, the potential SOC sink capacity for the low precipitation sites may be significantly decreased, thus increasing the overall curvature of the interaction.

Factors affecting the potential SOC sink capacity are likely similar to those influencing SOC concentration and pool discussed in chapter 3. Increase of MAP in arid climates where turf growth is limited by water availability, can increase biomass growth and subsequent C inputs. Additionally, at high MAP, increased microbial communities can decrease the SOC and increase releases of C as CO\(_2\) through microbial respiration.
Figure 4.14. The effect of mean annual precipitation on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of potential SOC sink capacity and precipitation p<0.001, DF=344, N=345).

Interaction of Mean Annual Temperature and Mean Annual Precipitation on the Potential Soil Organic Carbon Sink Capacity:

As both MAT and MAP were strong determinents of the SOC sequestration potential in home lawns, the interaction between these 3 variables can be vividly observed in 3-dimensional surface graphs (Figure 4.15). The highest potential SOC sink capacity occurred in soils with low MAT and for MAP ranging from 60-90 cm yr\(^{-1}\).

Similarly, the relationship of CDD and MAP on the potential SOC sink capacity in home lawns is depicted in Figure 4.16. The highest SOC concentrations occurred in
regions with low MAT, which were correlated with a small number of CDD, and moderate MAP. Optimal climatic conditions for SOC sequestration were in regions receiving MAP of 60-90 cm yr\(^{-1}\) and the lowest number of CDD.

Finally, the relationship of HDD and MAP on the potential SOC sink capacity of home lawns is depicted in Figure 4.17. The data indicated the highest SOC sequestration potential in regions with large number of HDD, and moderate MAP. Analysis showed the optimal climatic conditions for SOC sequestration in regions receiving MAP of 60-90 cm yr\(^{-1}\) and large number of mean annual HDD.
Figure 4.15. Surface graphs illustrating the potential soil organic carbon sink capacity to a depth of 15 cm over a range of mean annual temperatures and mean annual precipitations.
Figure 4.16. Surface graphs illustrating the potential soil organic carbon sink capacity to a depth of 15 cm over a range of mean annual precipitations and mean annual cooling degree days.
Figure 4.17. Surface graphs illustrating the potential soil organic carbon sink capacity to a depth of 15 cm over a range of mean annual precipitations and mean annual heating degree days.
Effects of Soil Nitrogen on Soil Organic Carbon Sequestration Rate and Sink Capacity:

In addition to the climatic factors affecting SOC sequestration in home lawns, numerous soil properties also impacted the SOC rate and sink capacity. Among these, soil N concentrations significantly impacted SOC concentration. The results presented in this section indicated that SOC sequestration rate is positively correlated with soil N concentration ($p<0.001$; Figure 4.18). An increase of soil N concentration by 0.1% increased the SOC sequestration rate by 0.75 Mg C ha$^{-1}$ yr$^{-1}$. Select soils included in this study indicated N concentrations approaching 0.6%, which could significantly impact the SOC sink capacity of home lawns.

Increase in SOC sequestration rate with increase in N concentration was likely due to decreased litter decomposition (Franklin et al., 2003) achieved through the alteration of microbial communities. This decrease in litter decomposition may result in higher concentrations of SOC retained in the soil and in turn greater rates of SOC sequestration. Results indicated that increased N additions, whether through return of clippings, organic amendments, or chemical fertilizers, may significantly increase the SOC sequestration rate in home lawns.
Figure 4.18. The effect of soil nitrogen concentration on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and N concentration p<0.001, DF=344, N=345).

The potential SOC sink capacity was also positively affected (p<0.001) by soil N concentration (Figure 4.19). Increase in soil N concentration by 0.1% in the root zone enhanced SOC sequestration potential by ~20 Mg C ha⁻¹, with an important impact on the total SOC sink capacity. This increase may be attributed to the interaction between soil N and SOC mineralization. Increases in soil N concentrations can significantly increase rates of SOC mineralization (Hopkins et al., 2008). Additionally, increase in N concentration results in improved turf growth and subsequent increases in biomass inputs.
Both of these factors can significantly increase the potential SOC sink capacity of home lawn soils.

Differences in soil N concentrations can occur due to a multitude of factors, an important among these being the addition of N fertilizers. Based on these results, increase in soil N concentrations through fertilizer additions may enhance SOC pools. N pools, however, can vary based on the type of fertilizer, amount applied, mode of application, slope gradient, and MAP. Differences in these factors may alter N concentrations across spatial scales, even for similar types and rates of fertilizer application.
Figure 4.19. The effect of soil nitrogen concentration on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of potential SOC sink capacity and N concentration $p<0.001$, DF=344, N=345).

**Effects of Soil Texture on the Soil Organic Carbon Sequestration Rate and Sink Capacity:**

Soil texture was another property strongly impacting the potential SOC sink capacity. Regression analysis of soil clay content on SOC sequestration rate in home lawns indicated an effect of texture on sequestration rate ($p<0.001$; Figure 4.20).

Additionally, silt content was positively correlated ($p=0.001$) with SOC sequestration rate (Figure 4.21). Increases in silt concentration by 10% increased the SOC sequestration
rate by as much as 0.28 Mg C ha\(^{-1}\) yr\(^{-1}\). Furthermore, total clay + silt content of home lawns indicated a greater correlation (p<0.001) with SOC sequestration rate (Figure 4.22). Total concentration of fine soil particles (silt + clay) may be a significant factor in SOC pool and rate of its enhancement. Trends indicated large initial increases in SOC sequestration rate with increase in fine soil particles, which continued at a decreasing rate until a fine particle content of 50-60%, after which SOC sequestration rate equilibrated and even decreased. At low fine particle concentrations, even a 10% increase in clay + silt concentration increased SOC sequestration rate by 0.57 Mg C ha\(^{-1}\) yr\(^{-1}\).
Figure 4.20. The effect of soil clay content on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and soil clay content \( p=\lt 0.001 \), DF=344, N=345).
Figure 4.21. The effect of soil silt content on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and soil silt content p=0.001, DF=344, N=345).
Figure 4.22. The effect of soil clay+silt content on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and soil clay+silt content p<0.001, DF=344, N=345).

While soil texture significantly impacted SOC sequestration rates, interaction on potential SOC sink capacity was contrary. Regression analysis of clay content on the potential SOC sink capacity indicated no impact (p=0.142; Figure 4.23). Similar results were observed for regressions analyzing potential SOC sink capacity by soil silt content (p=0.486; Figure 4.24) and clay + silt content (p=0.248; Figure 4.24). Based upon the interaction of soil texture and SOC concentration and pool as discussed in chapter 3, results observed for potential SOC sink capacity were expected due to relationship between these variables.
Figure 4.23. The effect of soil clay content on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sink capacity and soil clay content p=0.142, DF=344, N=345).
Figure 4.24. The effect of soil silt content on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sink capacity and soil silt content p=0.486, DF=344, N=345).
Figure 4.25. The effect of soil clay+silt content on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sink capacity and soil clay+silt content \( p=0.248 \), DF=344, N=345).

**Effects of Soil Bulk Density on Soil Organic Carbon Sequestration Rate and Sink Capacity:**

Another property which may significantly affect SOC sequestration in home lawns is the soil bulk density \( (\rho_b) \). Regression analysis indicated a positive correlation \( (p<0.001) \) between soil \( \rho_b \) and SOC sequestration rate (Figure 4.26). At low compaction, increases in \( \rho_b \) by 0.1 Mg m\(^{-3}\) increased SOC sequestration rate by 0.9 Mg C ha\(^{-1}\) yr\(^{-1}\). Previously, SOC concentration and pool illustrated initial increases due to increase in \( \rho_b \) followed by inhibition as soils surpassed \( \rho_b \) of 1.4-1.5 Mg m\(^{-3}\). This trend was expected.
as increased soil compaction can limit biomass inputs, especially at greater depths. The data on SOC sequestration rate, however, did not appear significantly inhibited by $\rho_b > 1.5 \text{ Mg m}^{-3}$. Regression analysis indicated SOC sequestration rate increasing at a decreasing rate, thus suggesting that extreme soil compaction can curtail or decrease the SOC sequestration rate. However, as all soils analyzed were managed home lawn turfgrasses, soil compaction was limited in sites sampled. Sampling of highly compacted turfgrasses ($\rho_b > 1.7 \text{ Mg m}^{-3}$), such as recreational areas may provide a better indication of the relationship among $\rho_b$ and SOC sequestration rate.
Figure 4.26. The effect of soil bulk density on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and soil bulk density $p<0.001$, DF=344, N=345).

Similar to the rate of SOC sequestration, potential SOC sink capacity was also affected ($p<0.001$) by soil $\rho_b$ (Figure 4.27). The response function indicated a polynomial interaction with increased $\rho_b$ resulting in potential SOC sink capacity increases at a decreasing rate. In contrast to the interaction among $\rho_b$ and SOC sequestration rate, regression analysis for potential SOC sink capacity indicated a point at which SOC sink capacity equilibrated ($1.6 \text{ Mg m}^{-3}$). As previously stated, the absence of turf soils with $\rho_b > 1.6 \text{ Mg m}^{-3}$ may limit the observed interaction among variables. The inclusion of
compacted turf soils in these analyses may strengthen the relationship among the potential SOC sink capacity and $\rho_b$.

Much like the SOC concentration data, it is probable there was an optimal range of soil $\rho_b$ because soil compaction at high density affected SOC sequestration. Again, absence of data points at $\rho_b > 1.6$ Mg m$^{-3}$ prohibited location of this optimal range. Nonetheless, increases in soil $\rho_b$ can lead to increases in the potential SOC sink capacity of home lawns.

Figure 4.27. The effect of soil bulk density on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of potential SOC sink capacity and soil bulk density $p<0.001$, DF=344, N=345).
Effects of Soil pH on Soil Organic Carbon Sequestration Rate and Sink Capacity:

Finally, acidity may also affect the soils capacity to sequester SOC. Regression analysis showed a positive correlation (p=0.007) between pH and SOC sequestration rate (Figure 4.28). Results indicated a slight increase in SOC sequestration rate with decrease in acidity. Observation of regression data indicated increase in SOC sequestration rate with decrease in acidity at pHs < 7.6. At pHs >7.6, no increase in SOC sequestration rate was observed, and a negative interaction may have occurred.

Increased rate of SOC sequestration with increase in soil pH was likely due to decreased plant productivity in acidic soils. As these soils became more basic, increased plant productivity led to increased OM inputs and SOC sequestration rate. Effect of pH, however, was small relative to other soil properties, with SOC sequestration rates increasing by less than 0.5 Mg C ha⁻¹ yr⁻¹ as soil pH increased from 5.6 to 7.6. Additionally, acidity changes can alter numerous soil properties such as decomposition rate, and microbial community. These soil-related parameters may be impacting the SOC sequestration rates in home lawns.
Figure 4.28. The effect of soil pH on the soil organic carbon sequestration rate in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of SOC sequestration rate and soil pH $p=0.007$, DF=344, N=345).

In contrast, the potential SOC sink capacity was not impacted by pH ($p=0.195$; Figure, 4.29). Again, based upon the lack of correlation between acidity and the SOC pool discussed in chapter 3, these results were expected. It is possible that more strongly acidic soils (pH<5.5) would indicate a significant impact on the potential SOC sink capacity of home lawns, however, none of the soils analyzed had pH's <5.6.
Figure 4.29. The effect of soil pH on the potential soil organic carbon sink capacity in home lawn turfgrasses to a depth of 15 cm (ANOVA for interaction of potential SOC sink capacity and soil pH $p=0.195$, DF-344, N=345).

Interaction of Climate and Soil Characteristics on the Soil Organic Carbon Sequestration Rate and Sink Capacity:

As described above, numerous soil and climatic factors affect the SOC sequestration rate and potential of home lawn turfgrasses within a region. Climatic aspects of MAT and MAP are important indicators of SOC sequestration in relation to soil properties such as N concentration, texture, $\rho_b$, and pH, which can alter SOC sequestration rates and pools.
While singular interactions among specific factors affect SOC sequestration, interaction among variables can alter both SOC sequestration rate and potential. On the basis of a best subsets regression analysis, interaction among significant variables (MAP, N concentration, $\rho_b$, pH, texture) on the SOC sequestration rate for 0-15 cm depth was analyzed. Analyses of regressions containing all significant variables can be viewed in Table 4.9.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mallows Cp</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC sequestration rate by N, $\rho_b$, $\rho_b^2$, CS, CS$^2$</td>
<td>36.1</td>
<td>0.49</td>
</tr>
<tr>
<td>SOC sequestration rate by P, $P^2$, N, CS, CS$^2$</td>
<td>9.0</td>
<td>0.53</td>
</tr>
<tr>
<td>SOC sequestration rate by P, $P^2$, N, $\rho_b$, $\rho_b^2$, pH, pH$^2$, CS, CS$^2$</td>
<td><strong>10.0</strong></td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 4.9. Best subset regression analysis for interaction of climatic and soil characteristics on soil organic carbon sequestration rate ($P$=precipitation, $N$=nitrogen concentration, $\rho_b$=bulk density, CS=clay+silt content, pH=pH; Cp values in bold indicate $C_p \leq p+1$).

On the basis of multiple regression analyses, model regressions were formed for the determination of SOC sequestration rate by climatic and soil properties (Table 4.10). Each model includes the significant variables as determined by the best subsets regressions.
Multiple Regression Analysis
0-15cm

<table>
<thead>
<tr>
<th>Variables</th>
<th>Regression Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P, N, $\rho_b$, pH, CS</td>
<td>SOC Seq Rate = -11.1 - 0.04P + 0.0003$P^2$ + 8.37N + 7.5$\rho_b$ - 1.29$\rho_b^2$ + 1.24pH - 0.1$pH^2$ - 0.04CS + 0.0003CS$^2$</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 4.10. Multiple regression analysis for interaction of climatic and soil characteristics on soil organic carbon sequestration rate (P=precipitation, N= nitrogen concentration, $\rho_b$=bulk density, CS=clay+silt content, pH=pH).

Interaction among variables influencing potential SOC sink capacity was also analyzed using a best subsets regression. Interaction among all significant variables (MAT/HDD/CDD, MAP, N concentration, $\rho_b$) on the potential SOC sink capacity for 0-15 cm depth was analyzed. Analyses of regressions containing all significant variables can be viewed in Table 4.11

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mallows Cp</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential SOC Sink Capacity T, T+$P$, $P^2$, N, $\rho_b$, $\rho_b^2$</td>
<td>8.0</td>
<td>0.66</td>
</tr>
<tr>
<td>Potential SOC Sink Capacity CDD, CDD$^2$ P, $P^2$, N, $\rho_b$, $\rho_b^2$</td>
<td>8.0</td>
<td>0.66</td>
</tr>
<tr>
<td>Potential SOC Sink Capacity HDD, HDD$^2$ P, $P^2$, N, $\rho_b$, $\rho_b^2$</td>
<td>8.0</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 4.11. Best subset regression analysis for interaction of climatic and soil characteristics on the potential soil organic carbon sink capacity (T=temperature, CDD=cooling degree days, HDD=heating degree days, P=precipitation, N= nitrogen concentration, $\rho_b$=bulk density; Cp values in bold indicate Cp≤p+1).
Utilizing the results of multiple regression analyses, model regressions were computed for the determination of potential SOC sink capacity by climatic and soil properties (Table 4.12). Each model includes the significant variables as determined by the best subsets regressions.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Regression Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T, T^2, P, P^2, N, \rho_b, \rho_b^2$</td>
<td>Pot SOC sink cap = $-211 - 0.19T - 0.006T^2 + 0.05P - 0.0003P^2 + \frac{188N + 231\rho_b - 56.1\rho_b^2}{1}$</td>
<td>0.66</td>
</tr>
<tr>
<td>$CDD, CDD^2 P, P^2, N, \rho_b, \rho_b^2$</td>
<td>Pot SOC sink cap = $-227 - 0.003CDD + 1 \times 10^{-6} CDD^2 + 0.09P - 0.0006P^2 + 191N + 251\rho_b - 63.9\rho_b^2$</td>
<td>0.66</td>
</tr>
<tr>
<td>$HDD, HDD^2 P, P^2, N, \rho_b, \rho_b^2$</td>
<td>Pot SOC sink cap = $-216 + 0.003HDD - 1 \times 10^{-7} HDD^2 + 0.06P - 0.0004P^2 + 187N + 222\rho_b - 52.3\rho_b^2$</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 4.12. Multiple regression analysis for interaction of climatic and soil characteristics on the potential soil organic carbon sink capacity (T=temperature, CDD=cooling degree days, HDD=heating degree days, P=precipitation, N= nitrogen concentration, $\rho_b$=bulk density).

**Hidden Carbon Costs of Home Lawn Turfgrass Maintenance:**

While home lawn management was less intense than management of golf courses and other turfgrass systems, it still required the use of several practices involving inputs based on fossil fuel combustion. One such practice was the addition of fertilizer, pesticides, and herbicides to maintain a healthy and cosmetically appealing lawn. Using the maintenance characteristics provided by home owners and assuming fertilizer application rates recommended by the production company facilitated estimates of the
HCC due to chemical application of 64.5 kg Ce yr\(^{-1}\) for each 1 ha of home lawn.

However, while the amount of P was assumed to be 0 since current standard fertilizers contain none, those applied over the last few decades did contain substantial concentrations of P. Additionally, fertilizers currently applied at the time of grass establishment still contain P as it is an important factor in root establishment. Thus, while standard fertilizers do not contain P, the estimations of HCC may undervalue the effect of chemical application on home lawns due to the current and former P sources discussed.

Furthermore, the HCC due to fertilizer application may be underestimated due to the low rate of fertilizer efficiency. This low efficiency can result in the volatilization of added N as nitrous oxide (N\(_2\)O), a gas with a global warming potential (GWP) 310 times higher than that of CO\(_2\). Emissions of N\(_2\)O from turfgrasses may be responsible for as much as 30% of national nitrous emissions (Kaye et al., 2004). Thus these emissions are also likely to increase the HCC associated with home lawn development. In order to minimize losses of N as N\(_2\)O, the use of slow release fertilizer has been proposed. However, some research indicates that slow release fertilizers can lead to even higher total N\(_2\)O emissions than urea (Maggiotto et al., 2000). Regardless of fertilizer type, application should occur when turf is dry and precipitation events are unlikely as these will increase N\(_2\)O emissions (Denmead et al., 1979).

Another major source of fossil fuel emissions from lawn maintenance is from mowing. On the basis of assumptions regarding the use of average home owner practices, the maintenance emissions due to lawn mower fuel combustion for one year was estimated at 189.7 kg Ce ha\(^{-1}\) yr\(^{-1}\). Based on these results, total maintenance
emissions for non irrigated home lawns in this study were 254.2 kg Ce ha\(^{-1}\) yr\(^{-1}\) (Table 4.13). As previously stated, no emissions were included for use of pesticides, fungicides, or herbicides due to the selection of lawn types. An average U.S. home lawn owner, however, was likely to apply one or all of these components which would increase the overall emissions due to maintenance practices and subsequently decrease the net climate mitigation potential of the system. Furthermore, the decomposition of grass clippings and additional biomass may result in the release of methane (CH\(_4\)), which has a GWP 21 times higher than that of CO\(_2\). While no current estimations of CH\(_4\) emissions exist for home lawn turfgrasses, these emissions may prove significant, especially in high precipitation regions. Thus, analysis of CH\(_4\) emissions from lawns may increase the total HCC due to lawn establishment. Additionally, many lawns throughout the country were irrigated on a regular basis. However, only 4 out of the 16 sites included in this study irrigated their lawns. Due to this low percentage and a lack of available information, total emissions on HCC due to irrigation were not estimated. All subsequent calculations were for non irrigated home lawn systems.
### Table 4.13

<table>
<thead>
<tr>
<th>Maintenance Practice</th>
<th>HCC of Maintenance Emissions (kg C eq ha(^{-1}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Fertilizer</td>
<td>63.6</td>
</tr>
<tr>
<td>P Fertilizer</td>
<td>0.0</td>
</tr>
<tr>
<td>K Fertilizer</td>
<td>0.9</td>
</tr>
<tr>
<td>Total Fertilizer</td>
<td>64.5</td>
</tr>
<tr>
<td>Mowing Fuel Combustion</td>
<td>189.7</td>
</tr>
<tr>
<td>Mean Total Emissions</td>
<td>254.2</td>
</tr>
</tbody>
</table>

Utilizing the maintenance emissions estimates determined above as well as the sequestration potential from each non irrigated site included in this study, the number of years until the amount of SOC sequestered is fully negated by the amount of C emissions was determined (Table 4.14). Due to the large variance in SOC sequestration among sites, the benefits of home lawn turfgrass establishment were evident for a period of between 79 to 409 years with an average duration of between 170-198 years for emissions to completely negate SOC sequestration. These data comprise an important calculation for a number of reasons. First, it allowed for the identification of optimal sites where home lawn turfgrass proliferation could benefit society through SOC sequestration. In areas where home lawns indicated a sequestration benefit for a period of as much as 409 years, conversion of depleted soils to home lawns may lead to SOC sequestration until a time when more permanent solutions to atmospheric CO\(_2\) enrichment take effect. Furthermore, it illustrated the importance of limiting maintenance emissions when possible to increase the mitigation benefits of home lawn establishment. For instance, the reduction of mowing practices can lead to low C
emission maintenance methods and increase the benefits of home lawn proliferation. Additionally, all estimations of HCC were for non irrigated home lawns. However, all lawns at four of the sites sampled in this study received daily year round supplemental irrigation. This is typical of lawns located in hot, arid climatic regions such as Nevada and Arizona. While the HCC associated with this level of water management were not calculated, it is assumed to be significant, limiting the C sink capacity of these soils. Thus, lawns located in regions requiring supplemental irrigation and other C intensive management practices should utilize xeriscape landscaping techniques which require little to no irrigation or other maintenance. These lawns are characterized by drought resistant plants (i.e., cacti) and can provide aesthetically pleasing landscapes that minimize or remove HCC. An example of a home lawn xeriscape located in Las Vegas, NV can be viewed in Figure 4.30.
<table>
<thead>
<tr>
<th>City</th>
<th>Mean Potential Soil Organic Carbon Sink Capacity (Mg C ha⁻¹)</th>
<th>HCC of Maintenance Emissions (Mg C e⁻¹ yr⁻¹)</th>
<th>Time until Sequestration = Emissions (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta, GA</td>
<td>29.3 ± 3.32</td>
<td>0.25</td>
<td>104-130</td>
</tr>
<tr>
<td>Dallas, TX</td>
<td>39.0 ± 1.70</td>
<td>0.25</td>
<td>149-163</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>46.3 ± 6.90</td>
<td>0.25</td>
<td>158-213</td>
</tr>
<tr>
<td>Duluth, MN</td>
<td>50.8 ± 3.55</td>
<td>0.25</td>
<td>189-217</td>
</tr>
<tr>
<td>Houston, TX</td>
<td>37.2 ± 2.52</td>
<td>0.25</td>
<td>139-159</td>
</tr>
<tr>
<td>Minneapolis, MN</td>
<td>96.3 ± 6.04</td>
<td>0.25</td>
<td>361-409</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>34.5 ± 4.63</td>
<td>0.25</td>
<td>119-157</td>
</tr>
<tr>
<td>Portland, ME</td>
<td>20.8 ± 1.00</td>
<td>0.25</td>
<td>79-87</td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td>60.9 ± 5.34</td>
<td>0.25</td>
<td>222-265</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>30.7 ± 2.33</td>
<td>0.25</td>
<td>113-132</td>
</tr>
<tr>
<td>Wichita, KA</td>
<td>48.3 ± 0.53</td>
<td>0.25</td>
<td>191-195</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>56.9 ± 3.86</td>
<td>0.25</td>
<td>212-243</td>
</tr>
<tr>
<td>Mean</td>
<td>45.9 ± 3.5</td>
<td>0.25</td>
<td>170-198</td>
</tr>
</tbody>
</table>

Table 4.14. Mean potential soil organic carbon sink capacity, maintenance emissions, and time for emissions to negate sequestration for 12 non irrigated sites throughout the U.S.

![Xeriscape in Las Vegas, NV.](image-url)
Potential Soil Organic Carbon Sink Capacity for Ohio and the United States:

Considering the total home lawn area, the SOC sequestration rate for Ohio and U.S. soils, and the calculated time for those soils to initially sequester SOC, the potential SOC sink capacity for both Ohio and U.S. home lawns was determined. Data indicated that all home lawn turf soils had a potential SOC sink capacity of 17.8 Tg C in the state of Ohio and between 443.1-549.5 Tg C in the U.S. (Table 4.15). These statistics, however, do not consider the maintenance emissions and HCC which decrease the net sequestration by these systems. For conversion among various metric and standard units see Appendix D.

<table>
<thead>
<tr>
<th>City</th>
<th>Mean Soil Organic Carbon Sequestration Rate (Mg C ha(^{-1}) yr(^{-1}))</th>
<th>Home Lawn Turfgrass Area (ha)</th>
<th>Time for Initial Sequestration (yrs)</th>
<th>Potential Soil Organic Carbon Sink Capacity (Tg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohio</td>
<td>2.3</td>
<td>322269</td>
<td>24</td>
<td>17.8</td>
</tr>
<tr>
<td>United States</td>
<td>2.8 ± 0.3</td>
<td>9847750</td>
<td>18</td>
<td>443.1-549.5</td>
</tr>
</tbody>
</table>

Table 4.15. Potential soil organic carbon sink capacity for all home lawn turfgrasses in the State of Ohio and the United States.

Maintenance emissions and HCC were estimated for all home lawns in Ohio on the basis of assumptions and procedures mentioned previously. Such calculations indicated HCC due to maintenance emissions at 20.8 Gg Ce yr\(^{-1}\) for fertilizer applications and 61.8 Gg Ce yr\(^{-1}\) for mowing fuel combustion under low management conditions for a total maintenance emission of 82.6 Gg Ce yr\(^{-1}\) for all Ohio home lawns (Table 4.16).
Additionally, the HCC due to maintenance emissions under high management conditions were estimated at 124.8 Gg Ce yr\(^{-1}\) for fertilizer applications and 123.6 Gg Ce yr\(^{-1}\) for mowing fuel combustion for a total maintenance emission of 248.4 Gg Ce yr\(^{-1}\) for all Ohio home lawns (Table 4.16).

<table>
<thead>
<tr>
<th>Maintenance Practice</th>
<th>HCC of Maintenance Emissions (Gg Ce yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Management</td>
</tr>
<tr>
<td>N Fertilizer</td>
<td>20.5</td>
</tr>
<tr>
<td>P Fertilizer</td>
<td>0.0</td>
</tr>
<tr>
<td>K Fertilizer</td>
<td>0.30</td>
</tr>
<tr>
<td>Total Fertilizer</td>
<td>20.8</td>
</tr>
<tr>
<td>Mowing Fuel Combustion</td>
<td>61.8</td>
</tr>
<tr>
<td>Mean</td>
<td>82.6</td>
</tr>
</tbody>
</table>

Table 4.16. Estimated carbon emissions due to home lawn turfgrass maintenance practices for the State of Ohio.

Similarly, HCC of maintenance emissions were estimated for all home lawns in the United States at 635.8 Gg Ce yr\(^{-1}\) for fertilizer applications and 1868.3 Gg Ce yr\(^{-1}\) for mowing fuel combustion under low management conditions, for a total maintenance emission estimation of 2504.3 Gg Ce yr\(^{-1}\) for all U.S. home lawns (Table 4.17).

Additionally, the HCC due to maintenance emissions under high management conditions were estimated at 3814.8 Gg Ce yr\(^{-1}\) for fertilizer applications and 3736.6 Gg Ce yr\(^{-1}\) for mowing fuel combustion for a total maintenance emission of 7551.4 Gg Ce yr\(^{-1}\) for all U.S. home lawns (Table 4.17). Again these estimations for both Ohio and U.S. home
lawn emissions do not account for emissions due to the volatilization of N fertilizer as N$_2$O or any possible methane emissions.

<table>
<thead>
<tr>
<th>Maintenance Practice</th>
<th>HCC of Maintenance Emissions (Gg Ce yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Management</td>
</tr>
<tr>
<td>N Fertilizer</td>
<td>626.7</td>
</tr>
<tr>
<td>P Fertilizer</td>
<td>0.0</td>
</tr>
<tr>
<td>K Fertilizer</td>
<td>9.1</td>
</tr>
<tr>
<td>Total Fertilizer</td>
<td>635.8</td>
</tr>
<tr>
<td>Mowing Fuel Combustion</td>
<td>1868.3</td>
</tr>
<tr>
<td>Mean</td>
<td>2504.1</td>
</tr>
</tbody>
</table>

Table 4.17. Estimated C emissions due to home lawn turfgrass maintenance practices for the United States

Again, these significant HCC and maintenance emissions reduced the net potential benefit of home lawn establishment. Accounting for both sequestration potential of newly formed turfs and average maintenance emissions included in this study, the time for sequestration to be completely negated through emissions was 223 years for Ohio lawns under low management conditions and as little as 71 years under high management conditions. Similarly, the time for sequestration to be completely negated through emissions for all U.S. lawns was estimated at 199 years for soils under low management and just 66 years for those under high management conditions (Table 4.18). The large range between time for sequestration to be negated by emissions for
soils under low and high management illustrates the importance of management practices on the potential of home lawns to mitigate GCC.

<table>
<thead>
<tr>
<th>City</th>
<th>Potential Soil Organic Carbon Sink Capacity (Tg C)</th>
<th>HCC of Maintenance Emissions (Tg Ce yr⁻¹)</th>
<th>Time until Sequestration = Emissions (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohio</td>
<td>17.8</td>
<td>0.08-0.25</td>
<td>71-223</td>
</tr>
<tr>
<td>United States</td>
<td>496.3</td>
<td>2.50-7.55</td>
<td>66-199</td>
</tr>
</tbody>
</table>

Table 4.18. Potential soil organic carbon sink capacity, maintenance emissions, and time for emissions to cancel out sequestration for the State of Ohio and the United States.

Management recommendations to Improve the Potential Soil Organic Carbon Sink Capacity:

The number of years to fully negate the SOC sequestered could be increased if the HCC of maintenance practices were reduced or curtailed. As an example, if fertilizer applications were either reduced or eliminated but SOC sequestration occurred at rates similar to when fertilizer was applied, the time until sequestration is negated would increase to as much as 297 years in Ohio soils under low management conditions and as much as 265 years in U.S. soils under low management conditions (Table 4.19). This is an improbable recommendation as it would require individual home owners nationwide to abandon fertilization strategies for decades. Furthermore, it would result in a reduction in the aesthetic quality of home lawns, which is of obvious importance to a large percentage of home owners. Additionally, these estimates are based on the assumption
that the SOC sequestration rates would remain significant even with the reduced rate of fertilizer input. As previously discussed, soil N concentrations significantly impacted the SOC pool. Thus complete abandonment of fertilization may decrease SOC pools and the potential SOC sink capacity of home lawns. However, additional research providing a precise fertilization rate that will optimize the SOC pool while minimizing the emissions due to HCC is needed. Additionally, if fertilizer must be applied, emissions due to HCC can be reduced by manual application of local products. This strategy would reduce the transportation HCC due to fuel consumption.

<table>
<thead>
<tr>
<th>City</th>
<th>Potential Soil Organic Carbon Sink Capacity (Tg C)</th>
<th>HCC of Maintenance Emissions (Tg C e yr⁻¹)</th>
<th>Time until Sequestration = Emissions (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohio</td>
<td>17.8</td>
<td>0.06-0.12</td>
<td>148-297</td>
</tr>
<tr>
<td>United States</td>
<td>496.3</td>
<td>1.87-3.74</td>
<td>133-265</td>
</tr>
</tbody>
</table>

Table 4.19. Potential soil organic carbon sink capacity, maintenance emissions, and time for emissions to cancel out sequestration for the State of Ohio and the United States under a mowing only maintenance program.

A more significant method of increasing the potential SOC sink capacity by home lawn establishment would be to identify techniques which decrease emissions associated with mowing the home lawn. Such practices under low management conditions could increase the time to fully negate SOC sequestration in the U.S. and Ohio's home lawn soils by nearly 400% (Table 4.20). As the average home lawn is ~0.08 ha, it is possible for home owners to utilize rotary mowers, which do not use fossil fuels. Such a strategy
could decrease the emissions due to HCC. However, should fossil fuel mowers be a
necessity, riding mowers (7.02 L ha\(^{-1}\)) should be preferred over walking mowers (9.35L
ha\(^{-1}\)) as they utilize less fuel (Sanu, 2008). Furthermore, the number of mowings per year
should be reduced as much as possible. This could be achieved by keeping grass at a
higher length and not mowing during hot summer weeks when grass growth is greatly
reduced. Additionally, keeping grass at a longer height may also increase the rooting
depth and the potential of the soil to sequester SOC.

<table>
<thead>
<tr>
<th>City</th>
<th>Potential Soil Organic Carbon Sink Capacity (Tg C)</th>
<th>HCC of Maintenance Emissions (Tg Ce yr(^{-1}))</th>
<th>Time until Sequestration = Emissions (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohio</td>
<td>17.8</td>
<td>0.02-0.12</td>
<td>148-890</td>
</tr>
<tr>
<td>United States</td>
<td>496.3</td>
<td>0.64-3.81</td>
<td>130-775</td>
</tr>
</tbody>
</table>

Table 4.20. Potential soil organic carbon sink capacity, maintenance emissions, and time
for emissions to cancel out sequestration for the State of Ohio and the United States
under a fertilization only maintenance program.

Irrigation of home lawns is also a significant source of HCC and maintenance
emissions for 10% of home lawn owners (Sanu, 2008). Emissions due to irrigation can
be minimized or eliminated by following a few recommendations. First, based on results
of the analyses from this study, irrigation should be limited to sites receiving less than
60cm yr\(^{-1}\) of precipitation. Additionally, water should be applied only when absolutely
necessary and the use of automatic timers avoided as they often lead to unnecessary
irrigation, even during rainfall/precipitation events. Furthermore, water should be added
when evapotranspiration is low, and, if possible, rain gages should be utilized to avoid the use of excess water and fuels for water transport.

Home lawn maintenance can be a C-intensive process depending on the methods and frequency of maintenance events. Table 4.21 lists a variety of maintenance recommendations that may decrease the HCC due to maintenance practices and increase the potential SOC sink capacity of home lawn turfgrass soils.
<table>
<thead>
<tr>
<th>Activity</th>
<th>Do’s</th>
<th>Don’t’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation</td>
<td>● Water only where annual precipitation &lt; 60cm/yr</td>
<td>● Water excessively following fertilization application</td>
</tr>
<tr>
<td></td>
<td>● Water only when necessary</td>
<td>● Water during the afternoon when temp and evaporation are high</td>
</tr>
<tr>
<td></td>
<td>● Water between 12am and 4am to minimize evaporation</td>
<td>● Use automatic timers that water even when raining</td>
</tr>
<tr>
<td></td>
<td>● Fix leaky/broken sprinkler heads and pipes promptly to avoid water</td>
<td>● Allow leaky sprinklers to ooze water, which may lead to increased</td>
</tr>
<tr>
<td></td>
<td>loss and fungal infections</td>
<td>fungicide use and water loss</td>
</tr>
<tr>
<td></td>
<td>● Utilize water from rain barrels</td>
<td></td>
</tr>
<tr>
<td>Fertilizer and Pesticide use</td>
<td>● Apply only when necessary</td>
<td>● Apply routinely regardless of necessity</td>
</tr>
<tr>
<td></td>
<td>● Apply by hand</td>
<td>● Use fuel driven equipment for application</td>
</tr>
<tr>
<td></td>
<td>● Buy products produced close to home to reduce transport emissions</td>
<td>● Buy products from out of state or region leading to high transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>emissions</td>
</tr>
<tr>
<td>Fuel use</td>
<td>● Use energy free rotary mowers</td>
<td>● Use fuel mowers when unnecessary, especially diesel burning inefficient equipment</td>
</tr>
<tr>
<td></td>
<td>● If fuel mower necessary</td>
<td>● Mow excessively</td>
</tr>
<tr>
<td></td>
<td>- Use riding over walking mower</td>
<td>● Keep grass excessively short</td>
</tr>
<tr>
<td></td>
<td>- Use hybrid energy efficient mower</td>
<td></td>
</tr>
<tr>
<td></td>
<td>● Mow only when necessary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Keep grass longer</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.21. Management recommendations to minimize carbon emissions due to turfgrass maintenance and maximize home lawn global climate change mitigation potential.

### 4.4 Conclusions

The data presented in this chapter explain the relationship between SOC sequestration rate, potential SOC sink capacity, climatic factors, and soil properties in home lawns nationwide. Additionally, it also described the potential of Ohio and U.S. home lawns to off-set C emissions in lieu of the estimated HCC of turfgrass maintenance,
and listed management recommendations to increase the potential SOC sink capacity of home lawns.

Following the establishment of home lawn turfgrasses, soils sequester SOC over time, however, rates of SOC sequestration vary substantially among sites. These variances are attributed to a range of both climatic variables and soil properties. While MAT had no impact on SOC sequestration rates, MAP did significantly alter rates in home lawns. This observation was contrary to hypotheses that SOC sequestration rate increases with decrease in MAT and increase in MAP. Results indicated a consistent decrease in SOC sequestration rate with increase in MAP, which may be due to alterations in soil microbial communities and the efficiency of fertilizer use at different MAP. Increases in MAP can significantly increase SOC decomposition by microbes. Additionally, increased MAP exacerbated losses by runoff and leaching of fertilizer, subsequently decreasing their use efficiency and lowering soil N concentrations.

Soil N concentrations also significantly altered the SOC sequestration rate of lawns. A linear correlation existed between N concentrations and SOC sequestration rate, probably due to decreased litter decomposition at higher N concentrations as well as improvement of biomass production. In addition to N concentration, soil acidity also affected SOC sequestration rates. Increases in pH were correlated with increase in SOC sequestration rate, however, the correlation was weaker than that with soil N concentration. These results contradicted the hypothesis that rate of SOC sequestration in U.S. home lawn turfgrasses increases with increase in soil acidity. As with MAP, changes in pH may be associated with fluctuations in decomposing microbial
communities. Furthermore, more acidic soils may limit grass productivity reducing the inputs through decreased biomass production.

Increase in soil $\rho_b$ was also highly correlated with the SOC sequestration rate, probably due to the increase in soil mass for SOC storage. However, the rate of SOC sequestration increased at a decreasing rate, indicating increase in SOC sequestration until soil compaction reduced the biomass-C inputs. Finally, in support of the hypothesis, SOC sequestration rate was significantly influenced by soil texture. In home lawns, increases in fine soil particles increased SOC sequestration rate. Regression analysis suggested significant increase in SOC sequestration rate until fine soil particles comprise approximately 50% of the bulk soil mass. Further presence of fine particles beyond this concentration, however, had no impact on SOC sequestration.

As was observed for SOC sequestration rate, the potential SOC sink capacity of U.S. home lawns was influenced by a range of climatic factors and soil properties. The MAP was a significant factor influencing the potential SOC sink capacity. However, in contrast to SOC sequestration rate, the regression indicated a polynomial function with increase in MAP in arid soils leading to increases in the potential SOC sink capacity followed by decrease with additional MAP beyond approximately 60 cm yr$^{-1}$. Such a functional relationship both proved and disproved the hypothesis that increase in MAP would increases SOC concentration. This non linear interaction is due to increased biomass productivity in arid soils, subsequently increasing inputs of biomass-C to the soil. The decrease in potential SOC sink capacity at higher MAPs, however, is probably due to the increase in litter and OM decomposing microbial communities. In contrast to SOC sequestration rate, MAT, HCC, and CDD all significantly affected the potential
SOC sink capacity of home lawns, supported the original hypotheses. Increases in MAT were highly correlated with decreased potential SOC sink capacity. The increase in MAT resulted in decreased photosynthetic activity which in turn limits biomass production and reduced inputs of OM.

The effects of soil N concentration and $\rho_b$ were examples of correlations similar to those for SOC sequestration rates. For similar reasons, increase in soil N concentration increased the potential SOC sink capacity. Furthermore, increase in $\rho_b$ initially increased the potential SOC sink capacity until compaction became significant and then limited further sequestration of SOC. Finally, contrary to the results observed for the SOC sequestration rate, soil texture was not significantly correlated with the potential SOC sink capacity.

Significant differences were also observed for both SOC sequestration rate and potential SOC sink capacity with variations in soil depth. The SOC sequestration rate and potential sink capacity both decreased with increase in soil depth, probably due to the decrease in N concentration and the decreased availability of biomass inputs with increase in depth.

Sites with highest rates of SOC sequestration were monitored where MAP was moderate (60-70 cm yr$^{-1}$), N concentrations were high, soil texture comprised $\geq$ 50% fine soil particles, and $\rho_b$ (~1.6 Mg m$^{-3}$) and pH (7.6-8.1) were optimal. Additionally, the potential SOC sink capacity of soils were the highest where MAT was low, MAP was moderate (60-70 cm yr$^{-1}$), N concentrations were high, and $\rho_b$ was optimal (~1.6 Mg m$^{-3}$). Based on these results, optimal conditions for the maximization of SOC sequestration rate and potential sink capacity occurred where MAT was low, MAP moderate (60-70 cm
yr\(^{-1}\), soil N concentrations were high, soil texture comprised \(\geq 50\%\) fine soil particles, and \(\rho_b (~1.6 \text{ Mg m}^{-3}\) and pH (7.6-8.1) was optimal. Maintaining soils as close to these conditions as possible can maximize the potential SOC sink capacity of U.S. home lawns and increase their potential to mitigate global climate change (GCC).

When compared with another major source of turfgrass growth, golf course development, home lawns had distinct SOC sequestration trends. The SOC sequestration rates were similar to those for rough treated golf course turfs. However, they were significantly lower than fairway treated golf turfs over the same area. This trend was not surprising because fairway turfs are intensively managed at levels far greater than home lawns. Additions of N throughout the year at rates and concentrations higher than in rough and home lawns was probably the reason for the high SOC sequestration rate. Furthermore, home lawns had significantly lower potential SOC sink capacities than both the golf course rough and fairway treated soils. While rates of SOC sequestration were similar for home lawns and rough treated soils, the rough grasses sequestered SOC for a longer period of time, leading to a significantly higher total SOC sequestration potential. The addition of N fertilizers throughout the year on home lawns may increase their potential SOC sink capacity. However, such an increase would come at a price, both in monetary cost of supplies and possible externalities associated with the HCC due to maintenance.

One of these externalities, the emission of greenhouse gases (GHG), is the result of the increased maintenance of home lawns and the subsequent high HCC. For lawns in this study, the addition of N fertilizers led to the emission of a significant amount of C. Limiting the amount of fertilizers used on home lawns may reduce these emissions.
significantly. However, the SOC pool was strongly impacted by N concentrations in the soil. Thus, if the addition of N containing fertilizer was reduced, the potential SOC sink capacity was also likely to be reduced. Ideally, fertilizer should be added in an amount that increases the net SOC sequestration potential while minimizing the emissions due to HCC. Additionally, the use of pesticides, herbicides, and fungicides should be limited whenever possible.

Secondly, fuel use due to yard mowing contributed nearly 300% more emissions than did fertilizer application. The weekly mowing of turfgrasses was responsible for over 250 kg Ce ha\(^{-1}\) yr\(^{-1}\). In order to increase the climate change mitigation potential of home lawn turfgrass systems, mowing should be limited by any means possible. Making sure to mow only when necessary and increasing the standard height of turfgrass are two ways to reduce fossil fuel combustion. Furthermore, increasing mowing height is likely to increase rooting depth and enhance SOC sequestration. This strategy could increase the total net potential of the lawn to sequester SOC while also reducing the HCC due to mowing. Additionally, the use of alternative forms of mowing could reduce the HCC associated with lawn mowing. The average U.S. home lawn is 0.08 ha. Lawns of this size could be mowed using non fossil fuel burning push rotary mowers, which could eliminate the fossil fuel component of the maintenance emissions while saving the home owner on fuel costs. Finally, if a fuel-powered mower is absolutely necessary, the use of a riding mower increases the fuel efficiency by 25% (Sahu, 2008). Thus, using a riding mower when available over a gasoline-powered push mower is a preferred method of lawn cutting.
Finally, irrigation was another substantial maintenance emission in arid regions of the country. As has been discussed, supplemental irrigation increased the SOC and eventually reduced it while also increasing HCC by fossil fuel combustion. In some regions of the country, however, turf establishment can only be accomplished through the use of supplemental irrigation. In these areas, irrigation should be applied at minimal rates to maintain optimal SOC sequestration. Excessive irrigation may not only be a waste of water and money, but also could reduce the potential SOC sink capacity of the yard and curtail many of the environmental benefits of such a system. Additionally, irrigation should not be used in humid regions with adequate MAP.

Utilizing the best estimates available for turfgrass area as well as SOC sequestration rates and longevity determined in this study, all home lawns for Ohio and the U.S. had a mean total SOC sink capacity of 17.8 and 496.3 Tg C, respectively. While this was a substantial amount which could significantly offset anthropogenic emissions, total emissions under low and high management regimes by HCC for home lawn maintenance in Ohio and the U.S. were estimated at 0.08-0.25 and 2.5-7.55 Tg Ce yr\(^{-1}\), respectively. This means that home lawns were a sink for atmospheric CO\(_2\) but at a decreasing rate as emissions over time fully negate the amount of SOC sequestered. However, if estimates of SOC sequestration and maintenance emissions are valid, under the amount of SOC sequestered can be completely negated by HCC in as little as 71 years for Ohio and 66 years for the U.S.. Thus, emissions due to HCC must be minimized to increase the net potential of home lawn turfgrass systems to sequester SOC and mitigate GCC. Additionally, it must be noted that any long term benefits achieved through the sequestration of SOC by home lawns can be negated at any point through soil
disturbance. For instance, tillage or stripping of the soil can quickly re-release a large portion of the SOC sequestered as CO₂, thus eliminating its long term potential to mitigate atmospheric GHG enrichment. Thus, in order to maintain the sequestration benefits provided by home lawns, the soil structure must be maintained over time.

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Chapter 5: Summary and Future Research Needs

5.1 Summary

The rapid expansion in human population and subsequent increase in fossil fuel use has resulted in global climate change (GCC). Recently, turfgrass soils have shown the capacity to sequester soil organic carbon (SOC) and may prove a valuable asset in climate change mitigation. This research was conducted with the following objectives, to: (i) determine the capacity of U.S. home lawn turfgrass systems to sequester SOC over time, (ii) ascertain the relationship between key soil properties and climatic variables and assess the potential SOC sink capacity of U.S. home lawns (iii) determine the potential of Ohio and U.S. home lawns to off-set carbon emissions in relation to hidden carbon costs (HCC), (iv) provide management recommendations to increase the potential SOC sink capacity of U.S. home lawn turfgrasses, and (v) determine current research gaps and prioritize future research needs into turfgrass systems.

The first of these five objectives was addressed in chapter 2 through an in-depth analysis of the SOC sequestration capacity of home lawn turfgrasses over time. The data indicated that home lawns have the capacity to sequester SOC over time following establishment, confirming the first hypothesis. The SOC sequestration to 15 cm depth occurred in all regions studied following the conversion from a native land use. Soils sequestered significant amounts of SOC over a relatively short period of time after which
time SOC concentration stabilized for roughly 40-50 years and then further increased. The initial time for SOC concentration to stabilize was 18 years for all depths analyzed. However, the time for initial sequestration ranged from 11 to 41 years among all study sites. Rates of SOC sequestration also varied, ranging between 0.01 and 0.70% with differences among locations and depths. Generally, both the rates of SOC sequestration and total SOC concentration decreased with increase in soil depth with the majority of lawns sequestering SOC to the concentration of 2-3%. Exceptionally high SOC concentrations following initial sequestration were measured in the soils of Minneapolis, MN (5.6%), Wooster, OH (3.4%), Denver, CO (3.2%), and Duluth, MN (3.1%). Alternately, exceptionally low SOC concentrations were observed in Atlanta, GA (1.5%). Soil inorganic carbon (SIC) concentrations were also significant in the hot, dry climates of both Dallas, TX (2.2%), and Las Vegas, NV (2.1%). Nevertheless, home lawn turfgrasses throughout the nation had the capacity to sequester SOC over time upon conversion from a native land use (i.e., agricultural soils, grasslands).
The second objective was discussed in chapters three and four through description of empirical relationships between key soil properties and climate on the SOC concentration, pool, sequestration rate, and potential sink capacity. Through sampling and data analyses, a range of soil and climatic properties were identified which significantly affect SOC concentration (Figure 5.1). Soils developed in different ecoregions varied in SOC concentration and pool due to differences in climate. Mean annual temperature (MAT) influenced SOC concentration, pool and potential sink capacity, where increase in MAT decreased each of these variables (Figure 5.1). Soils developed in lower MAT had higher SOC concentrations, pools, and potential sink capacities than those in higher MAT. However, MAT did not significantly affect the overall rate of SOC sequestration in home lawns. Similarly, mean annual precipitation (MAP) significantly affected the SOC concentration, pool, sink capacity, and also the
sequestration rate (Figure 5.1). While MAT had little effect on the SOC sequestration rate, increase in MAP decreased the SOC sequestration rate. This trend was most likely due to the effect of MAP on numerous other soil properties such as the increase in runoff and leaching of soil nitrogen (N). Additionally, there existed a curvilinear relationship between SOC concentration, pool, and potential SOC sink capacity. In all of these cases, increase in MAP increased SOC concentration up to a critical threshold level. Beyond the threshold, however, SOC concentration, pool, and sink capacity were all constrained by any further increase in MAP. This trend was likely due to the interaction of MAP with other soil factors such as N concentration, as well as the increase in aboveground and belowground biomass with increase in MAP in the drier regions. Thus, the interaction of both MAT and MAP was at least partially responsible for the SOC pool within the home lawn turfgrasses. These data both proved and disproved the third hypothesis that SOC pool and rate of sequestration increase with decrease in MAT and increase in MAP. However, based on these results, soils with exceptionally high SOC concentrations and sequestration potential were most likely to be in regions with the lowest MAT and optimal MAP of 60-90 cm yr\(^{-1}\). These results were consistent with soils in Minneapolis, MN, which had the highest SOC sink capacity of all soils analyzed.

In addition to climatic variables, numerous key soil properties influenced SOC concentration and pool (Figure 5.1). Most importantly, soil N concentration was positively correlated with SOC concentration, pool, sequestration rate, and potential SOC sink capacity. Increases in soil N concentration at all sites was strongly correlated with increases in all four of these SOC attributes. These trends supported the conclusion that soil N concentration was one of the major driving forces influencing the potential of
home lawns for SOC sequestration. This observation was of importance because home lawns were almost always accompanied by the addition of artificial N through fertilizer applications. Thus, increased fertilizer use was likely to increase grass growth and SOC sequestration.

Soil bulk density ($\rho_b$) also affected SOC concentration, pool, sequestration rate, and the potential SOC sink capacity (Figure 5.1). Similar to the MAP, a nonlinear interaction existed between $\rho_b$ and SOC concentration, pool and potential sink capacity. Increases in soil $\rho_b$ initially increased each of these parameters because of significant increases in the area for C sink capacity. However, as with MAP, once a threshold was attained, further increase in $\rho_b$ limited SOC sequestration. Indeed, increased soil compaction can decrease the overall SOC concentration, pool, and potential sink capacity of home lawns.

Similarly, soil pH (reaction) also impacted SOC sequestration rate. However, pH had no interaction with SOC concentration, pool, or the potential sink capacity (Figure 5.1). Yet, pH was strongly correlated with the rate of SOC sequestration. For acidic soils, increase in soil pH increased SOC sequestration rate. These data support and contradict the second hypothesis that SOC pool and sequestration rate increase with increase in soil acidity.

Finally, soil texture impacted SOC sequestration rate but not the SOC concentration, pool or potential sink capacity of home lawns (Figure 5.1). The SOC sequestration rate increased with increase in silt and clay + silt contents. Such an increase in fine soil particles increased aggregation and SOC sink capacity. However, results were contradictory to the second hypothesis, which stated an increase in both SOC
sequestration pool and rate of sequestration occurs with increase in clay content. While clay content was not correlated with SOC pool, clay + silt contents were strongly correlated.

Changes in these properties could alter the quality of home lawn soils in a variety of ways. Thus, these climatic factors and soil properties were important determinants of SOC concentration, pool, sequestration rate, and potential sink capacity. Multiple regression analyses indicated that home lawns can sequester SOC over a variety of soil types and climatic regimes. Such multiple regressions indicated that the SOC concentration of home lawns for a diverse range of soils and climates can be estimated by polynomials in Eq. 5.1 (p<0.001; $R^2=0.64$), Eq. 5.2 (p<0.001; $R^2=0.64$), and Eq. 5.3 (p<0.001; $R^2=0.64$), where $T$=MAT, $P$=MAP, HDD= heating degree days, CDD=cooling degree days, $N$=soil N concentration (%), and $\rho_b$=bulk density (Mg m$^{-3}$).

\[
[SOC]=-15.3-0.06T+0.002T^2+0.01P-0.00008P^2+8.96N+22.5\rho_b-7.81\rho_b^2\text{...........(Eq. 5.1)}
\]
\[
[SOC]=-16.1-8x10^{-6}+1x10^{-7}HDD^2+0.01P-8x10^{-5}P^2+8.93N+22.9\rho_b-7.97\rho_b^2\text{...........(Eq. 5.2)}
\]
\[
[SOC]=-16.1-0.0002CDD+1x10^{-7}CDD^2+0.0P-0.0001P^2+9.15N+23.0\rho_b-8.0\rho_b^2\text{....(Eq. 5.3)}
\]

Similarly, the SOC pool can be estimated by using Eq. 5.4 (p<0.001; $R^2=0.71$), Eq. 5.5 (p<0.001; $R^2=0.71$), and Eq. 5.6 (p<0.001; $R^2=0.71$), where $T$=MAT, $P$=MAP, HDD= heating degree days, CDD=cooling degree days, $N$=soil N concentration (%), and $\rho_b$=bulk density (Mg m$^{-3}$).
SOC Pool = -213 - 1.4T + 0.04T^2 + 0.27P - 0.002P^2 + 214N + 281\rho_b - 85.0\rho_b^2 ..............(Eq. 5.4)
SOC Pool = -233 + 2 \times 10^{-4} HDD + 1 \times 10^{-7} HDD^2 + 0.3P - 0.002P^2 + 213N + 291\rho_b - 88.6\rho_b^2 .... (Eq. 5.5)
SOC Pool = -228 - 0.005CDD + 2 \times 10^{-6} CDD^2 + 0.342P - 0.002P^2 + 218N + 286\rho_b - 87.4\rho_b^2 ...(Eq. 5.6)

Additionally, the SOC Sequestration rate in home lawns can be estimated by using Eq. 5.7 (p<0.001; R^2=0.54), where P=MAP, N=soil N concentration (%), pH=soil pH, CS=clay + silt content, and \rho_b=bulk density (Mg m^{-3}).

\[ \text{C Seq Rate} = -11 - 0.04P + 0.003P^2 + 8N + 7.5\rho_b - 1.3\rho_b^2 + 1.2pH - 1pH^2 - 0.04CS + 0.003CS^2. (Eq 5.7) \]

Finally, the potential SOC sink capacity for home lawn turfgrasses can be estimated by Eq. 5.8 (p<0.001; R^2=0.66), Eq. 5.9 (p<0.001; R^2=0.66), and Eq. 5.10 (p<0.001; R^2=0.66), where T=MAT, P=MAP, HDD= heating degree days, CDD=cooling degree days, N=soil N concentration (%), and \rho_b=bulk density (Mg m^{-3}).

\[ \text{Pot C sink cap} = -211 - 0.19T - 0.006T^2 + 0.05P - 0.0003P^2 + 188N + 231\rho_b - 56.1\rho_b^2 ..........(Eq. 5.8) \]
\[ \text{Pot C sink cap} = -227 - 0.003CDD + 1 \times 10^{-6} CDD^2 + 0.09P - 0.0006P^2 + 191N + 251\rho_b - 64\rho_b^2. (Eq. 5.9) \]
\[ \text{Pot C sink cap} = -216 + 0.003HDD - 1 \times 10^{-7} HDD^2 + 0.06P - 4 \times 10^{-4}P^2 + 187N + 222\rho_b - 52\rho_b^2(Eq5.10) \]
These regression equations highlight the importance of key soil properties and climatic factors as determinants of SOC pool and related parameters in the home lawn soils of the U.S.

Chapter 4 specifically addressed the third objective of determining the gross and net potential of home lawns in Ohio and the U.S. to sequester SOC in the context of the HCC of lawn maintenance. The potential SOC sink capacity differed among locations and soil types. The gross potential SOC sink capacity ranged from $20.8 \pm 1.0 \text{ Mg C ha}^{-1}$ in Portland, ME to $96.3 \pm 6.0 \text{ Mg C ha}^{-1}$ in Minneapolis, MN with an average nationwide potential of $45.8 \pm 3.5 \text{ Mg C ha}^{-1}$. The establishment and regular maintenance of these turfs had significant HCC, estimated at 254.2 kg carbon equivalents (Ce) ha$^{-1}$ yr$^{-1}$ with major emissions by fuel combustion from mowing (189.7 kg Ce ha$^{-1}$ yr$^{-1}$), and N fertilizer use (64.5 kg Ce ha$^{-1}$ yr$^{-1}$). Thus, for the average home lawn, SOC sequestration was fully negated through HCC by 170-198 years post establishment. Extrapolating these data to the entire State of Ohio estimated the potential SOC sink capacity of 17.8 Tg C for all home lawns in Ohio. However, HCCs for the state were estimated between 82.6 and 248.4 Gg Ce yr$^{-1}$ depending on management type. Accounting for both sequestration and HCC, sequestration was completely negated through HCC by 71-223 years after lawn establishment. Further extrapolation of these data to the entire United States estimated the potential SOC sink capacity of 496.3 Tg C for all home lawns nationwide. However, HCCs for the country were estimated between 2504.1 and 7551.4 Gg Ce yr$^{-1}$ depending on management regime. Accounting for both sequestration and HCC, the SOC sequestration was completely negated through emissions by 66-199 years after lawn establishment. These results confirmed the fourth hypothesis that SOC sequestration
occurred for around 30 years, after which soils became saturated and were a source of C due to the HCC of maintenance. However, the further increase in SOC concentration after ~60-70 years post establishment was unexpected.

While the home lawns significantly sequestered SOC for hundreds of years, the results must be viewed in light of a few significant concerns. First, lawn SOC concentration stabilized within a period of ~18 years. Thus, the majority of lawns in the U.S. have already attained the steady state C value and may no longer absorb additional atmospheric carbon dioxide (CO$_2$). Thus, the only way to increase the potential of these soils is to reduce or completely eliminate HCC of maintenance emissions, which slowly negate the benefits of SOC sequestration. Secondly, the HCC related to emissions from irrigation, the application of fungicides, herbicides, and insecticides, as well as emissions of N$_2$O and CH$_4$ were neither determined nor taken into account for any of the previous analyses. About 10% of home lawns, however, apply supplemental irrigation and thus the energy used for this maintenance practice may decrease the net SOC potential in arid regions. Additionally, many home owners use pesticides/fungicides/herbicides. While the HCC of these inputs were not included in this work, their national use may also decrease the overall net SOC potential of home lawn soils throughout the U.S..

Additionally, all sites used in this study returned clippings to the lawn. Many homeowners may choose to bag and discard clippings, which can decrease SOC concentrations and reduce the net SOC potential of home lawns. Finally, numerous soil properties were not measured in this study due to logistical restrictions. Concentrations of soil phosphorous (P), and sulfur (S) for instance were not analyzed but may significantly contribute to the SOC sequestration much like the impact of soil N
concentration. Thus a range of additional soil properties may alter SOC concentration and pool at across ecoregions.

The fourth objective of this study, to provide future management recommendations to increase the potential SOC sink capacity of U.S. home lawn turfgrasses, was discussed in chapter 4. Mowing recommendations included such strategies as utilizing rotary mowers that do not use fossil fuels, keeping grass height higher for a longer period, and, when necessary, utilizing riding rather than walking fuel-based mowers. Furthermore, recommendations for fertilizer and pesticide use included the application of local products by hand only when absolutely necessary and avoiding/reducing the use of any fuel-based inputs and applications. Finally, recommendations for irrigation included, among other things, irrigating only when mean annual precipitation (MAP) is less than 60cm yr\(^{-1}\), applying irrigation at the time of the day when evapotranspiration is low, and recycling rainwater to limit water transport costs. Following these (as well as other recommendations) could create more efficient home lawns. More efficient methods and/or the reduction of C-intensive maintenance practices could increase the potential SOC sink capacity of home lawns and improve their benefits to climate change mitigation.

Finally, the fifth objective of determining the current knowledge gaps and identifying and prioritizing suggestions for future research needs are discussed below. This section addresses knowledge gaps, and identifies future research to strengthen the research data.
5.2 Future Research Needs

This study has answered numerous questions regarding SOC sequestration in home lawn turfgrasses. However, it has also identified new knowledge gaps which could benefit from future research. Experimentation into some of these questions may not only improve the scientific knowledge of home lawn turfgrass systems, but also provide more efficient and healthy turfs with a higher capacity to sequester atmospheric CO₂.

One such question is that of the effect of N fertilizers on SOC sequestration in home lawn turfgrasses. Lawns throughout the country are fertilized with N fertilizers applied at a range of rates. While one home owner may choose to fertilizer once per year, another may apply N four times a year. Results indicated that soil N concentrations are strongly correlated with increased SOC concentration. Thus, the question arises about the magnitude of SOC sequestration through higher levels of N fertilizers. For instance, will the addition of fertilizer four times per year result in four times the amount of SOC sequestered? Does the use efficiency of fertilizer decrease with the increase in rate, and what is the optimal rate of N application for soil specific situations?

Additionally, home lawn fertilizer use is associated with SOC emissions related to HCC for the production, transport, and often the application of these fertilizers. Thus, if the increased number of fertilizer applications increases the SOC pool, is the increase adequate to offset the emissions from the HCC associated with increased application? Determining the optimal fertilizer use rate per year to optimize SOC sequestration and minimize the HCC of fertilizer application could produce a more efficient lawn with a stronger climate change mitigation potential. Bormann et al. (2001) analyzed the HCC of home lawn maintenance and suggested the term "Freedom Lawn". This type of lawn
consists of turfgrasses receiving no chemical fertilizers, yet could increase net SOC sequestration through the elimination of the HCC of fertilizers. However, a complete elimination of N fertilizer may deplete the SOC pool, reducing the lawns SOC sequestration potential. Thus, research to identify the optimal N fertilizer application rate to maximize the potential SOC sink capacity of home lawn turfgrasses is essential.

In relation to N fertilizers, the management of home lawn grass clippings is another theme that needs additional research. All lawns studied in this research returned clippings while mowing. However, many home owners choose to bag clippings and have them removed, thus limiting the return of aboveground biomass to the soil. Qian et al. (2010) showed that removal of clippings could result in a loss of SOC concentrations of between 11-59% over a 50yr period. Thus perpetual removal of clippings may reduce the rate and magnitude of SOC sequestration. Therefore, clippings management should be researched in conjunction with the fertilizer use for determination of an optimal combination of clippings return and N fertilizer rate. If N additions prove to be an important factor in SOC sequestration, it is feasible that return of clippings may partially or completely substitute for chemical fertilizers.

While much attention has been given to the N concentration and additions into the soil, other essential nutrients have not yet been researched. Being a major nutrient, N has been widely researched. However, from a SOC sequestration standpoint, additions of other nutrients, (i.e., P and S) have not received the attention these elements deserve. Future research into the potential SOC sink capacity of home lawn turfs may benefit from analysis of soil P and S, which are an important factor in the humification of biomass in agroecosystems (Himes, 1998; Saroa and Lal, 2003). Indeed, P and S concentrations
may be an important part of the SOC sequestration potential of home lawns. Research into these nutrients is important because many companies (i.e., Scotts Lawn Service) have decided to remove all P from their standard fertilizers (Scotts, 2011). This removal may inhibit SOC sequestration, and additional study into these interactions is necessary.

In addition to nutrient contents in the soil, the importance of pesticides, fungicides, and herbicides to SOC sequestration must also be studied. While the use of these chemicals is mostly cosmetic, their importance to the potential SOC sink capacity of home lawn turfs is not understood. None of the studied sites used these chemicals as part of their lawn management programs. Due to the lack of these chemicals, however, many of the lawns were heavily infested with weeds such as dandelions (Taraxacum officinale) which may affect the overall composition and biomass of the lawn. In response to this observation, the question arises as to the effect of these weeds on the gross/net SOC concentration and pool. If the effect is purely cosmetic then refraining from the use of such chemicals can enhance the potential SOC sink capacity However, if not using such chemicals inhibit SOC sequestration, using optimal rates of these chemicals may be beneficial. Either way, additional research into this topic is important to determining the optimal climate change mitigation potential of home lawns.

In addition to chemical management, mowing management is another theme that needs further research, including the mowing height. Increased mowing height can significantly increase the root biomass by over 30\% (Shahba, 2010). That being the case, large benefits could be accrued from increased mowing height in typical lawns. Increased root biomass could increase SOC concentration and thus increase the potential
SOC sink capacity of home lawns. Additionally, a higher mowing height may reduce HCC of fuel use as mowing could be done less frequently.

Another factor which may contribute to the SOC sequestration potential of home lawns is the choice of grass species grown in soil/climatic specific situations. The SOC sequestration rate varies among grass species (Qian et al., 1997; 2010). However, home lawn grass species are not chosen for their SOC sequestration potential but for their adaptation to grow in a specific ecoregions. While it is likely that the optimal grass for a region may result in the highest potential SOC sink capacity, it may not be the case in all ecoregions. Additionally, some climatic regions are suitable for a range of grass species. In these regions, the grass species which sequester the highest amount of SOC and the least HCC should be grown to maximize the climate change mitigation potential. However, research information as to which grass species sequester the most SOC in a specific ecoregion is not currently available and thus research determining the SOC sequestration potential of a range of grasses in diverse regions could be extremely important. Furthermore, regions where a variety of species could be planted may benefit from the establishment of lawns with diverse species. A typical lawn is kept monoculture for aesthetic/cosmetic purposes. However, seeding numerous species may actually increase the potential SOC sink capacity of the lawn by creating a system resilient to biotic and abiotic stresses.

Yet another management practice that could benefit from additional research is the supplemental irrigation. There is an optimal range of MAP to optimize the SOC sequestration potential. Thus, lawns in extremely arid locales (i.e., Las Vegas, NV) benefit from supplemental irrigation. Without additional water, grass growth in these
regions would be severely curtailed and SOC sequestration would be small or negative. However, supplemental irrigation allows enhanced production and increase in SOC over time. While this may be obvious for arid climates, additional research is needed into the effect of supplemental irrigation in subhumid and humid climates. The data of this study suggest optimal SOC sequestration potential at MAP of 60-90 cm yr\(^{-1}\). Thus, if soils receiving 50cm yr\(^{-1}\) are irrigated with just 10cm yr\(^{-1}\) to achieve an optimal moisture regime, will this enhance the net SOC sequestration potential of those soils and what are the additional HCC of irrigation? These questions can be effectively addressed by additional research into the importance of an optimal water regime.

This study has focused solely on the interaction among turfgrasses and soil C sequestration in home lawns, however, the vast majority of yards are characterized by additional biotic species which may influence the overall C sink capacity of lawns. Future investigation into the ability of trees, shrubs and other common yard plant species to enhance C sequestration could show an increased potential of home lawns to sequester SOC.

Finally, all research conducted in this study has been done to 15 cm depth. Most research on turfgrasses to date has also been conducted to 15 or 20 cm depth. Nonetheless, SOC sequestration can occur to much greater depths, especially over time (Follett et al., 2001b; Gebhart et al., 1994). Thus, additional research as to the depth of SOC sequestration in home lawn turfgrasses may show that the benefits of grass establishment are underestimated because of shallow depth of soil analysis. If turfs can sequester SOC to depths of 20 cm or more, then the overall potential of these soils to sequester SOC may be much greater than hitherto reported.
Research into the SOC sequestration potential of home lawn turfgrasses and their climate change mitigation potential is a fairly new endeavor. Thus, additional research is needed to produce lawns that not only look aesthetically pleasing but also function in a manner consistent with environmental preservation and restoration.

References


References


APPENDIX A

Nonlinear regressions of home lawn development on SOC concentration
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over an 83 year period in Albuquerque, NM (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=7, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.08</td>
<td>4.04</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.05</td>
<td>2.83</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.06</td>
<td>2.48</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.04</td>
<td>2.08</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Albuquerque, NM.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 93 year period in Cheyenne, WY (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=9, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr(^{-1}))</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.18</td>
<td>3.84</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.11</td>
<td>2.59</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.08</td>
<td>2.16</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.12</td>
<td>1.94</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Cheyenne, WY.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 93 year period in Dallas, TX (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=10, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.18</td>
<td>4.00</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.06</td>
<td>2.43</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.09</td>
<td>1.99</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.15</td>
<td>2.14</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Dallas, TX.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over an 83 year period in Denver, CO (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=8, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.19</td>
<td>6.02</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.11</td>
<td>3.76</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.05</td>
<td>2.65</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.11</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Denver, CO.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 100 year period in Duluth, MN (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=10, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.09</td>
<td>3.65</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.14</td>
<td>3.32</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.18</td>
<td>2.88</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.13</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Duluth, MN.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 100 year period in Houston, TX (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=9, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.17</td>
<td>4.20</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.09</td>
<td>2.54</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.08</td>
<td>1.83</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.06</td>
<td>1.57</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Houston, TX.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 73 year period in Las Vegas, NV (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=6, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=6, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=6, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=6, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.29</td>
<td>3.99</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.19</td>
<td>2.72</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.24</td>
<td>2.53</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.22</td>
<td>2.17</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Las Vegas, NV.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 100 year period in Orlando, FL (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=10, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.20</td>
<td>3.42</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.22</td>
<td>2.72</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.10</td>
<td>1.73</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.07</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Orlando, FL.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 73 year period in Phoenix, AZ (One-way ANOVA with Tukey’s post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=8, N=3 for each sample year).

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<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.23</td>
<td>3.50</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.12</td>
<td>2.15</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.05</td>
<td>2.03</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.11</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Phoenix, AZ.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 93 year period in Portland, ME (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=7, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=7, N=3 for each sample year).

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<tr>
<th>Depth</th>
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<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.11</td>
<td>2.84</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.06</td>
<td>2.29</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.06</td>
<td>2.08</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.05</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Portland, ME.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over an 83 year period in San Francisco, CA (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm \( p < 0.001 \), DF=9, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm \( p < 0.001 \), DF=9, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm \( p < 0.001 \), DF=9, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm \( p < 0.001 \), DF=9, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr(^{-1}))</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.70</td>
<td>6.10</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.40</td>
<td>3.57</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.21</td>
<td>2.29</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.11</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in San Francisco, CA.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 93 year period in Seattle, WA (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=9, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=9, N=3 for each sample year).

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<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.03</td>
<td>4.01</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.01</td>
<td>2.75</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.09</td>
<td>2.27</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.09</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Seattle, WA.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 93 year period in Wichita, KS (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 2.5-5 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=8, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=8, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.27</td>
<td>4.07</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.10</td>
<td>2.56</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.11</td>
<td>2.19</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.11</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Wichita, KS.
The effect of home lawn turfgrass development on the soil organic carbon concentrations at depths of 0-2.5 cm, 2.5-5 cm, 5-10 cm, and 10-15 cm over a 100 year period in Wooster, OH (One-way ANOVA with Tukey's post test, for interaction of SOC concentration by year at a depth of 0-2.5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentrations by year at a depth of 2.5-5 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 5-10 cm p<0.001, DF=10, N=3 for each sample year; SOC concentration by year at a depth of 10-15 cm p<0.001, DF=10, N=3 for each sample year).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Max Rate of SOC Change (% yr⁻¹)</th>
<th>Mean SOC Following Initial Sequestration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5 cm</td>
<td>0.25</td>
<td>5.13</td>
</tr>
<tr>
<td>2.5-5 cm</td>
<td>0.20</td>
<td>3.75</td>
</tr>
<tr>
<td>5-10 cm</td>
<td>0.21</td>
<td>3.30</td>
</tr>
<tr>
<td>10-15 cm</td>
<td>0.14</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Maximum rate of soil organic carbon change and mean soil organic carbon concentration following initial sequestration for four depths in Wooster, OH.
APPENDIX B

Charts of mean SOC concentration by depth in home lawn turfgrasses
Mean soil organic carbon concentration following initial sequestration at 4 depths in Albuquerque, NM (One-way ANOVA with Tukey’s post test, for all interactions of SOC concentration by depth  p<0.001, DF=3, N=15 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Cheyenne, WY (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth p<0.001, DF=3, N=21 for 0-2.5 cm, 5-10 cm and 10-15 cm depth, and N=24 for 2.5-5cm depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Dallas, TX (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth \( p<0.001 \), DF=3, N=24 for each depth, means with different letters are significantly different at \( p<0.05 \). Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Denver, CO (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth  p<0.001, DF=3, N=21 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Duluth, MN (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth p<0.03, DF=3, N=30 for 0-2.5 cm depth and N=27 for 2.5-5 cm, 5-10 cm and 10-15 cm depths, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Houston, TX (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth p<0.001, DF=3, N=24 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Las Vegas, NV (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth  p<0.001, DF=3, N=18 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Orlando, FL (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth  $p<0.001$, DF=3, N=24 for 0-2.5 cm depth and N=21 for 2.5-5 cm, 5-10 cm, and 10-15 cm depths, means with different letters are significantly different at $p<0.05$. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Phoenix, AZ (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth  p<0.001, DF=3, N=21 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Portland, ME (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth  p<0.001, DF=3, N=18 for 0-2.5 cm depth and N=21 for 2.5-5 cm, 5-10 cm, and 10-15 cm depths, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in San Francisco, CA (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth  p<0.001, DF=3, N=21 for 2.5-5 cm depth and N=24 for 0-2.5 cm, 5-10 cm, and 10-15 cm depths, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Seattle, WA (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth, \( p<0.001 \), DF=3, N=24 for 0-2.5 cm depth and N=27 for 2.5-5 cm, 5-10 cm, and 10-15 cm depths, means with different letters are significantly different at \( p<0.05 \). Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Wichita, KS (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth p<0.001, DF=3, N=21 for each depth, means with different letters are significantly different at p<0.05. Error bars = standard error).
Mean soil organic carbon concentration following initial sequestration at 4 depths in Wooster, OH (One-way ANOVA with Tukey's post test, for all interactions of SOC concentration by depth p<0.001, DF=3, N=24 for 0-2.5 cm depth and N=27 for 2.5-5 cm, 5-10 cm, and 10-15 cm depths, means with different letters are significantly different at p<0.05. Error bars = standard error).
APPENDIX C

3-dimensional surface graphs of climate on SOC concentrations
Surface graphs illustrating soil organic carbon concentrations at a depth of 2.5-5 cm over a range of mean annual temperatures and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentrations at a depth of 2.5-5 cm over a range of number of mean annual heating degree days and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentrations at a depth of 2.5-5 cm over a range of number of mean annual cooling degree days and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentration at a depth of 5-10 cm over a range of mean annual temperatures and mean annual precipitations
Surface graphs illustrating soil organic carbon concentration at a depth of 5-10 cm over a range of number of mean annual heating degree days and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentration at a depth of 5-10 cm over a range of number of mean annual cooling degree days and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentration at a depth of 10-15 cm over a range of mean annual temperatures and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentration at a depth of 10-15 cm over a range of number of mean annual heating degree days and mean annual precipitations.
Surface graphs illustrating soil organic carbon concentration at a depth of 10-15 cm over a range of number of mean annual cooling degree days and mean annual precipitations.
APPENDIX D

Table of units and conversions used throughout the study
<table>
<thead>
<tr>
<th>Metric Unit</th>
<th>Metric Equivalent</th>
<th>Standard Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gram (g)</td>
<td>-</td>
<td>0.002 lbs</td>
</tr>
<tr>
<td>Kilogram (kg)</td>
<td>1000 g</td>
<td>2.2 lbs</td>
</tr>
<tr>
<td>Megagram (Mg)</td>
<td>$1 \times 10^6$ g or 1 metric tonne</td>
<td>1.1 short tons</td>
</tr>
<tr>
<td>Gigagram (Gg)</td>
<td>$1 \times 10^9$ g or 1000 metric tonnes</td>
<td>1102 short tons</td>
</tr>
<tr>
<td>Teragram (Tg)</td>
<td>$1 \times 10^{12}$ g or 1 million metric tonnes</td>
<td>$1.1 \times 10^6$ short tons</td>
</tr>
<tr>
<td>Petagram (Pg)</td>
<td>$1 \times 10^{15}$ g or 1 billion metric tonnes</td>
<td>$1.1 \times 10^9$ short tons</td>
</tr>
<tr>
<td>Hectare (ha)</td>
<td>10000 m$^2$</td>
<td>2.47 acres</td>
</tr>
</tbody>
</table>

List of metric units, conversions between them and standard equivalents for all units utilized in this study.