Carbon Sequestration in Soils at Carleton College: Current Practices and Future Recommendations

Geology 258
Geology of Soils
Fall 2014

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Table of Contents:

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GEOL 258: Geology of Soils
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24 November 2014

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I. Introduction and Purpose

Climate change and global warming are imminent threats to the world, and all possible steps to slow their progress must be taken. The removal of the greenhouse gas CO_2 from the atmosphere through carbon sequestration in soils is one such step, and could be carried out locally at Carleton College (Northfield, MN). This document will provide an assessment of the potential impact that carbon sequestration by soils at Carleton could have by presenting Geographic Information Systems (GIS) data on the area of campus that could be converted to a groundcover that would maximize carbon sequestration by soil. The soils of Carleton's campus will be assessed for their carbon sequestration potential. Concrete actions that should be taken in order to maximize carbon sequestration will be outlined, and comparisons to Carleton's peer college campus' equivalent programs will be made.

II. GIS Data for Carleton College

Using the program ArcMap to study campus GIS, we determined the relative areas of campus land uses (Table 1). Our field areas was bounded by the arboretum to the north and west, First Street to the south (except for near the river where we extended the boundary to Second street), and the cannon river to the west (Figure 1). This area was split into buildings, water, paved areas, athletic fields, and land available for alteration (Figure 2). Campus athletic fields were broken out because they must remain in turf for athletics use. Pavements were also recognized because areas in pavement should remain as such in order to reduce erosion in those areas from compaction thanks to foot and vehicle traffic. While the Lyman Lakes could be altered into a wetland, this option was not strongly considered due to its lack of feasibility, and water was therefore considered to be another non-alterable land. Current buildings are considered areas for application of green roofs (discussed further below). The remaining land was labeled as alterable. These are areas covered with vegetation that could be manipulated in order to improve their carbon sequestration levels. Assuming an average soil density of 1.33g/cm^3 and an A horizon depth of between .18 m and .33 m (the A-horizon depth listed for the Estherville, the mapped soil on Carleton's campus), the sequestration of .5% more organic carbon in Carleton's alterable soils would result in between 441 and 808 tons of sequestered carbon (depending on the A-horizon depth).

Type	Percent	Area (m^2)	Acres
% Buildings	8.34	54,281	13.41
% Water	7.35	47,833	11.82
% Pavements	13.48	87,732	21.68
% Fields	27.45	126,496	31.26
% Alterable Land	43.37	334,274	82.60
Totals	100.00	650,617	160.77

Table 1. GIS analysis of Carleton College's land use.

Figure 1. GIS image of our field area. This includes most contiguous campus-owned lands, excluding the arboretum. Information gathered from the Carleton college's GIS campus dataset.

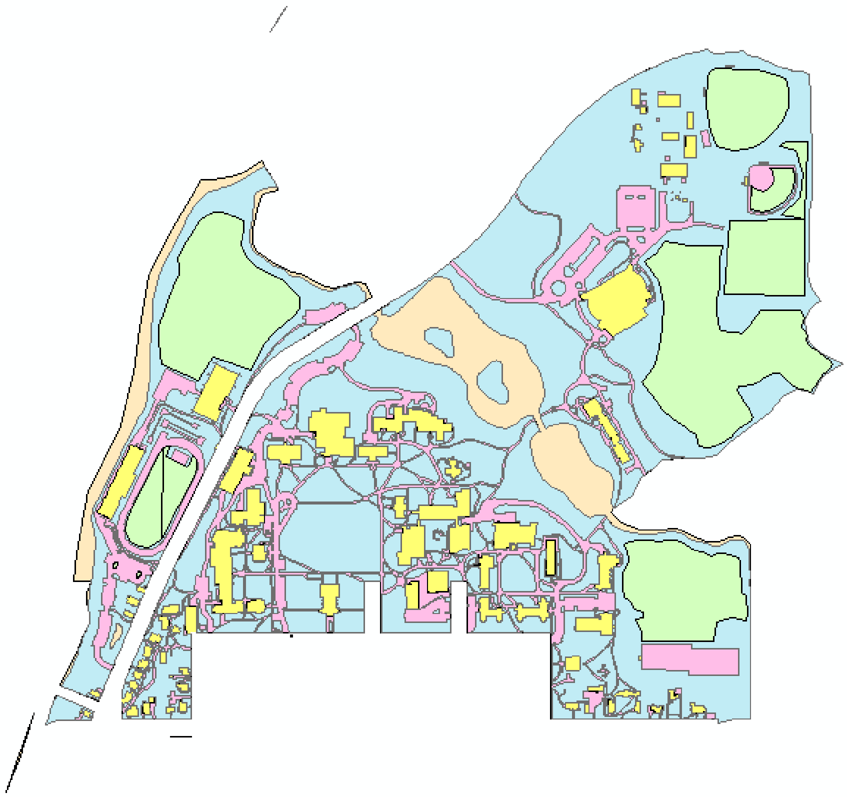

Figure 2. Carleton campus broken down into different land-use areas: yellow=buildings; tan=water; pink=paved areas; green=athletic turf; and blue=alterable land.

III. LOI

Loss on Ignition (LOI) experiments reveals the amount of organic material in a soil. Organic matter and organic carbon are directly proportional at a ratio of 1:1.72, which allows for a calculation of organic carbon for these soils. This means that LOI experiments are a strong indicator of carbon sequestration. Data for the Sibley Marsh and McKnight Prairie show average surficial LOI values of 15.84% and 2.97%, respectively. Therefore, organic carbon is determined to be 9.21% and 1.73%. Campus soils are not as organic rich as marsh soils, nor are they are eroded as the sloped soils of McKnight Prairie. We can therefore designate 1.73% and 9.21% carbon content as extreme bounds on the average carbon content of topsoil on campus.

IV. Carleton's Soils

Observations from soil pits dug in Carleton's Arboretum, which provides a relatively undisturbed setting to study native soils, were used to inform our knowledge of soils on Carleton's central campus area. Carleton's campus is thought to contain approximately five soil series. Each series' individual properties affect its ability to sequester carbon within its soil. These properties are outlined below.

A. *Estherville*

Areas of campus of relatively high elevation and flat slope are believed to be part of the Estherville soil series. The Estherville series has a fairly thick A-horizon, at 18 to 33 cm, which (in part thanks to its flat topography) has the potential to accumulate organic material and thus sequester carbon. However, the Estherville's larger grain size may inhibit retention of organic material and the associated carbon sequestration. Specifically, the A-horizon of the Estherville has a sandy loam texture, and grain size increases further with depth.

B. *Colo/Rushriver*

The Colo and Rushriver soil series encompass the areas of campus that sit in the Cannon River's floodplain. Because of their alluvial source, these soils have extremely thick A-horizons: the Colo's A-horizon is 75 to 102 cm and the Rushriver's A-horizon is up to 127 cm thick. These thicknesses, combined with the soils' poor drainage, increase the potential for organic material storage and the accompanying carbon sequestration. The Colo A-horizon's texture of silty clay loam would be especially good for retaining organic material and sequestering carbon; the Rushriver's A-horizon is a very fine sandy loam, which might not be as ideal for trapping organic material because of its bigger grain size.

C. Hawick

The areas of campus with greater slopes are probably members of the Hawick soil series. This series' higher slope (2-70%) may cause erosion of the topsoil, which is a likely cause of the thinner A-horizon of 18 cm. These factors may decrease the retention of organic material in the A-horizon. Additionally, the A-horizon clay content is only 2-15%, and sand content is 60-90%; therefore the grain size in the Hawick is too large to be ideal for organic matter retention.

D. *Hayden*

Carleton's athletic fields behind the Recreation Center (near the Hill of Three Oaks) are believed to be part of the Hayden series. This series features a very thin (up to 10 cm) A-horizon, which could decrease carbon sequestration potential. It also is very well-drained, which could encourage decomposition and further minimize the amount of carbon sequestered in the soil.

V. Summaries of Review Papers

A major project in the Geology of Soils class (Fall term 2014) was the completion of a literature review. The review paper assignment was intended to expose students both to the process of writing a literature review and to introduce the concept of carbon sequestration in soils. Students were divided into six groups and instructed to investigate topics regarding the optimization of soil carbon sequestration. These topics were land practices, riparian zone soils, turf grass, soil erosion, ecosystem and molecular properties of soils, and plant types. Each paper described how the topic relates to carbon sequestration. Brief summaries of each paper, with emphasis on suggestions for Carleton's campus, are below.

A. *Land Practices - Donovan and Shapiro (2014)*

Carleton College's campus land practices influence the health of the soil and how much carbon the soil can sequester. In order to have the greatest impact on carbon sequestration by soils, it is important to tailor these practices to optimize soil health. For instance, Carleton already bans building on steep slopes and driving and parking vehicles on these slopes in an effort to minimize erosion and soil loss. However, these regulations should be more strictly enforced for more successful carbon sequestration. Another management practice that increases carbon sequestration in soil is leaving fallen leaves on the ground to decompose. The Grounds department already mulches and redistributes leaves to most parts of campus, which should work favorably toward carbon sequestration. But for aesthetic purposes, leaves are removed from the Bald Spot; leaving these leaves on the soil would improve carbon sequestration in this area. Ultimately, restoring prairie grass to Carleton's campus would be the most effective management strategy for carbon sequestration purposes, because prairie grass's deep and dense root systems contain high levels of carbon. However, this would be a very large transition to make and may be very impractical for that reason.

B. *Riparian Zone Soils - Kaufman and Viesselman (2014)*

Given the presence of the Cannon River and Spring Creek adjacent to Carleton College's campus, the interplay of water and land is important to consider in carbon sequestration. Riparian zones are ecotones that exist at these boundaries between water and land. When land is covered permanently or periodically with water, it can sequester more than any other land. This is because decomposition is restricted in water-logged soils by the lack of oxygen. Therefore proper management of our riparian zones must be an important part of carbon mitigation strategies. This could include impoundment of water and the creation wetlands along the Cannon River on Carleton lands.

C. *Turf Grass - McLellan (2014)*

Some areas, such as the athletic fields on campus, must remain as turf grass for functional purposes. Even with this limitation, measures can be taken to maximize the carbon sequestered by the soil beneath the turf grass. For instance, sufficient nitrogenous fertilizer application will increase turf grass's biomass, which will in turn increase its carbon sequestration. Leaving clippings on the turf after it is cut will also add a source of nitrogen to the turf grass and increase the amount carbon that can be stored by the soil. The carbon footprint of turf grass is heavily influenced by the management practices, such as mowing and fertilizing, that act as a source of carbon. Studies show that these practices cause turf grass to transition from a sink to a source of carbon between 5 and 30 years (Selhorst and Lal, 2011; Kong et al., 2014) Minimizing these impacts will improve turf grass's net impact on carbon sequestration.

D. *Soil Erosion - Davis and Hornor (2014)*

Soil erosion has been shown to serve as both a source and a sink of atmospheric carbon, as the process of erosion involves many opportunities for eroded soil to either become mineralized (released to the atmosphere) or deposited and buried. However, at each step of the erosional process, a number of complex factors can affect whether the eroded soil organic matter will be an eventual source or sink. These factors include variations in the agent of erosion, topography, soil properties, moisture content, and the severity of erosion. Soil erosion as it relates to carbon sequestration is still somewhat poorly understood, and accurate predictions about the eroded soil's fate cannot necessarily be made. As such, no recommendations for Carleton can really be made regarding the intersection of erosion and sequestration.

E. *Plant Types - Black et al. (2014)*

Different plants sequester carbon with varying amount of success. Fast-growing plants input high levels of carbon due to their large biomass of active roots, but they are also often short-lived and decompose quickly, which decreases the amount of carbon that they can sequester. Slow-growing plants, on the other hand, contain more carbon within the plant structure and decompose slowly, but don't contribute as much carbon to the soil through root respiration as fast growing plants. This trade-off between slow-growing and fast-growing plants is often affected by the specific biome and by the quality of the leaf litter, so it is difficult to know exactly which plant growth rate would be most favorably to Carleton College's campus. We do, however, know that in southeastern Minnesota, the plants that will sequester the most carbon are C4 grasses with high belowground biomass and prairie legumes that fix nitrogen.

F. *Ecosystem and Molecular Properties - Van Fleet and Stein (2014)*

Properties of soils, both at the molecular level and at the ecosystem level, that make soils more likely to sequester high levels of carbon should be investigated. At the ecosystem level, variables such as climate, vegetation, soil structure, soil heterogeneity, and plant roots influence organic carbon levels in soil. Overall, afforestation and grassland restoration efforts have both been found to increase soil organic carbon, though results can depend on the climate and the type of plants involved. At the molecular level, various compounds may be more recalcitrant than others, but more research is needed in order to make confident conclusions in this regard. Application of these findings to Carleton's campus is difficult without further research, because current knowledge is often specific to an ecosystem and a single tested variable.

III. Options for Carbon Sequestration

A. Carleton's Peer Institutions

Carleton College recognizes 25 other liberal arts colleges as its 'peer institutions,' used for strategic planning purposes (Carleton College, 2014). We searched the sustainability websites and Climate Action Plans of these peer institutions to research what practices they were currently implementing to sequester carbon. Of these 25 schools, only five have mentions of carbon sequestration as a strategy to reduce carbon emissions: Beloit College, Hamilton College, Macalester College, Swarthmore College, and Wellesley College. Additionally, Evergreen State College has worked extensively to implement carbon sequestration as a strategy to offset their carbon footprint. We will briefly outline the efforts of each of these six institutions.

1. Beloit College: Beloit, WI

Beloit College offers a "Sustainability Fellows" program, which is a summer program open to current Beloit students. This fellowship entails an 8-week development and research opportunity to implement campus or community-based sustainability programs. One of the 2014 sustainability fellows analyzed the trees in the city of Beloit to estimate their carbon storage potential. This information could be further used by the college and community to monitor changes in carbon sequestration over time (Beloit College, 2014).

2. Hamilton College: Clinton, NY

Hamilton College's 2009 Climate Action Plan cited an '09 graduate's study regarding the carbon sequestration potential of campus lands. The student stated that land currently in use as a golf course and croplands have the potential to sequester 547.7 metric tons of carbon annually. The CAP states that the College will examine this option in the coming years, though it mentions the challenges that massive changes in land use would present (Hamilton College, 2009).

3. Macalester College: St. Paul, MN

Macalester College currently operates two green roofs, a 300 ft^2 roof atop the link between Turck and Doty Halls and a 1,350 ft^2 roof atop Kagin Commons. These roofs offer space for carbon sequestration to occur via plant growth, in addition to reducing the school's carbon footprint by insulating the buildings (Macalester College, 2009).

4. Swarthmore College: Swarthmore, PA

The notes from Swarthmore's CAPcom (climate action plan committee) suggest that carbon sequestration is being considered as a method to obtain carbon offsets. One suggestion was to reforest Crum Woods, a woodland adjacent to the College's Scott Arboretum. However, the notes cite the difficulty of quantifying the exact amount of carbon sequestered and the need to invest in a third party should the sequestration project take hold (Swarthmore College, 2012).

5. Wellesley College: Wellesley, MA

In 2004, Wellesley College quantified their carbon storage potential on campus to be 150 tonnes of carbon annually. Because only minor changes in land use have occurred since the primary analysis, it's safe to assume that their carbon storage potential has not been significantly altered. Because the College is already aware of its current carbon storage potential, a precedent has been set to maintain, if not improve, that potential (Wellesley College, 2008).

6. Evergreen State College: Olympia, WA

In 2007, Evergreen committed to reforest 30 percent of its lawns before 2018. According to Evergreen's director of sustainability, however, the project has been delayed because the grounds department is worried students will climb and fall out of the trees, the college uses campus lawns for commencement, and the extra shade from reforestation would make Evergreen's already overcast campus too dreary (Morgan, 2014).

B. Possible Future Work

Each paper makes important suggestions for Carleton's carbon sequestration policy. These policies primarily include, but are not limited to:

—Modify construction regulations to protect soil (Donovan and Shapiro, 2014)
—Leave leaves where they fall (Donovan and Shapiro, 2014)
—Restore wetlands on Colo and Hamal series (Kaufman and Viesselman, 2014)
—Fertilize turf grass sufficiently, leave grass clippings (McLellan, 2014)
—Plant more prairie legumes and C4 grass types (Black et al., 2014)

In our research, we came across two other possible techniques not covered by these breadth of these papers: Green roofs and Sustainable Drainage Systems (SuDS).

1. Green Roofs

Given that Carleton has over 50,000 m^2 of roof space available, Carleton has the potential for using green roofs as a carbon sequestration technique. Green roofs have been shown to on average sequester ~165 g/m^2 of carbon in aboveground biomass (Getter et al., 2009). The same report demonstrated that these green roofs also sequestered ~100 g/m^2 of carbon in belowground substrate each year for the first two years. If Carleton College committed one tenth of its building surfaces to green roofs, we could sequester 21.84 tons of carbon in two year. *Sedum album* is a good plant to use in green roof projects due to its elevated aboveground sequestration compared with other species of the genus (Getter et al., 2009).

2. SuDS

SuDS can also be used to sequester carbon on Carleton's campus. SuDS are used to address issues of excess water in an environment (which Carleton College must also do given past flooding events). However, they have the potential to also aid in carbon sequestration on campus (Warwick and Charlesworth, 2011). The addition of a vegetated drainage basin could address both these concerns. Water-retention ponds can trap up to 17,000 g/m^2 of carbon each year in bottom sediments, though figures have been recorded as low as 148 g/m^2 of carbon per year (Dowling et al., 2008). Though the smaller ponds have been shown to sequester more carbon per square meter than larger ponds. A 15 m^2 pond could trap 5000 g of carbon per year in vegetation (Charlesworth, 2010). Therefore, five 15 m^2 ponds on Carleton's campus could sequester .02 tons of carbon a year.

IV. Conclusion

Carbon sequestration has become an essential topic, thanks to global warming that is driven in part by rising atmospheric CO_2. Carbon sequestration by soils on campus is therefore something that Carleton College, as an environmentally conscious institution, needs to work toward. This report documents findings from GIS analysis that approximately 43.37% of Carleton's central campus area can be altered in order to maximize the potential carbon capacity of the soils. An assessment of Carleton's soils finds that most have at least some qualities that are conducive to soil carbon sequestration on campus. Recommendations for the management of campus' alterable areas are summarized from more extensive reports (see appendices). Finally, an assessment of Carleton's peer institutions' actions toward carbon sequestration reveals that the steps outlined in this report to sequester carbon on a college campus are relatively innovative. Even so, further steps could be taken: implementation of green roofs and sustainable drainage basins are two such measures.

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Fall | 14

Carbon Sequestration and its Limits at Carleton College

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Geology of Soils, Mary Savina

Abstract

One current method to mitigate elevated atmospheric CO2 levels is carbon (C) sequestration within soils. In current scholarship, papers regarding carbon sequestration focus on large-scale agricultural lands and there is a gap in research when it comes to exploring the limits of C sequestration within urban soils. In order to bridge this gap, this paper explores the limitations and capacity of C sequestration within Mollisols and mollic Alfisols and synthesizes numerous agricultural C sequestration strategies in order to create C sequestration strategies specific to the Carleton campus.

Introduction: C sequestration as a method for mitigating climate change

There has been a drastic increase in the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs) since the industrial revolution (Lal 2004). The atmospheric concentration of CO_2 has increased from 280 ppmv in 1750 to 395 ppmv in 2014 and is currently increasing at the rate of 1.5 ppmv/year or 3.3 Pg C/year (Lal 2004). This anthropogenic enrichment of CO_2 in the atmosphere, along with the radiative forcing of additional greenhouse gases (CH_4, N_2O, and CFCs), has led to an increase in the average global surface temperature of 0.6 degrees Celsius since the late 19th century, with the current warming rate of 0.17 degrees C/decade (Lal 2004). This rate is so rapid that our Earth's ecosystems cannot properly adjust. As a result our world is faced with unpredictable climate patterns, heightened sea levels, acidifying oceans, insect outbreaks, dangerous air quality, and many more environmental dangers that pose a threat to our global society (Metz et al., 2007). In order to begin solving the problem of climate change, we must look to the carbon cycle: if we can better understand the sources, sinks, and flow of carbon within our global ecosystem, we can develop strategies for reducing atmospheric C concentrations and ultimately mitigate climate change.

Carbon Sequestration in Soil

The global carbon cycle consists of five principal C pools: the oceanic (760 Pg C), the geologic (coal, oil, and gas, 5000 Pg C), the pedologic (soil, 2500 Pg C), the atmospheric (760 Pg C), and the biotic (560 Pg C) (Lal 2004). This paper will focus on the pedologic carbon pool in order to address the ways we can mitigate carbon emissions through carbon sequestration within the soil.

The pedologic C pool is comprised of two main components: soil organic carbon (SOC) and soil inorganic carbon (SIC). SIC refers to the carbon in the soil derived from lithogenic and pedogenic sources and SOC refers to carbon derived from soil organic material (SOM)[1]. While SIC is important to the global C pool, in considering C sequestration under agroecosystems, the SOC pool is more vulnerable to land use degradation and has historically been more affected by land use (Lal 1999). Therefore, as we consider C sequestration and land use, we will focus on the dynamics of SOC within the global C cycle.

SOM stabilization is an important component of C storage. Within soils, SOM can be stabilized within the soil in three ways: chemical stabilization (the chemical binding between SOM and soil clay and silt particles); physical protection (the soil aggregate barrier between microbes and enzymes); and biochemical stabilization (SOM stabilization as a result of its own chemical composition (lignin content and polyphenols) (Six et al. 2002). These three realms of SOM stabilization can be synthesized into four measurable SOM pools: a biochemically-protected C pool; a silt and clay protected C pool; a microaggregate protected C pool; and an

[1] SOC and SOM both play an important role in measuring the C degradation of soil. In fact, SOC can be determined from SOM values. Although SOC/SOM ratios vary by soil type, on average SOM contains 58% of organic (Perie and Ouime, 2007) Therefore SOM content is indicative of SOC values.

unprotected C pool (which consists of recently decomposed plant residue that is not closely associated with soil minerals) (Six et al., 2002). Each pool has its own dynamics and stabilization methods. For example, biochemically protected C, with its inherent chemical complexity, inhibits decomposition and is often considered non-hydrolyzable (incapable of undergoing hydrolysis)(Leavitt et al. 1996). Chemically protected C is preserved through its association with silt and clay particles. Here, the amount of C protection increases as silt and clay proportions increase in the soil (Hassink, 1997). In physically protected C, soil aggregates protect SOM and act as a physical protective barrier to control microbial turnover of SOM (Six et al. 2002). Lastly, unprotected C, the least stable C pool, is most sensitive to land management practices.

Although these mechanisms are important in determining SOM stability, the limitations of soil to physically protect organic matter has not yet been determined and the capacity of soils to preserve organic matter has not yet been quantified (Hassink 1997). Repeated plowing, as is often done in low-input systems, accentuates mineralization (Lal 1998). Mineralization (the complete breakdown of organic compounds into CO_2, H_2O and plant nutrients (Schimel and Bennett, 2004)) is a major processes in SOC depletion. A second predominant degradative process is erosion. An important determinative factor in C depletion is topography. On steep slopes soil erosion is the principal cause of SOM depletion while on flat soils mineralization predominates (Lal 2004). Overall as a result of converting natural lands to agroecosystems, the depletion of the global SOC pool is significant, with C depletion estimated at 50 to 100 Pg (Lal 1999, 2004).

History of C Storage and Losses in the Great Plains

Prior to the arrival of European settlers, prairie ecosystems of the Great Plains accounted for nearly 1.7 million km^2 across central North America (DeLuca and Zabinski, 2011). Because agriculture was not a common practice, these soils had been undisturbed for thousands of years. This allowed for massive levels of C to accumulate through biomass production, decomposition and ultimately storage as stable organic matter. The staple of the prairie ecosystem was native tall grass (NTG). Given that these soils were not affected by crop exportation, it is calculated that about 3-5 Mg of C is retained in the soil each year as metabolic C. Compounding this annual storage rate over 5000-8000 years results in estimates of total C storage of about 70-130 Mg ha^{-1} in the top 20-30 cm and 130-357 Mg ha^{-1} throughout the entire profile of the average NTG prairie (DeLuca and Zabinski, 2011). This is equivalent to the amount of C currently stored in the geologic C pool (Lal 2004). Given the current state of C level in Midwestern soils, it is obvious that something had to change to release almost 130-357 Mg $ha-^{1}$ out of the soils. This change came in the form of the Manifest Destiny and the American spirit to settle the frontier.

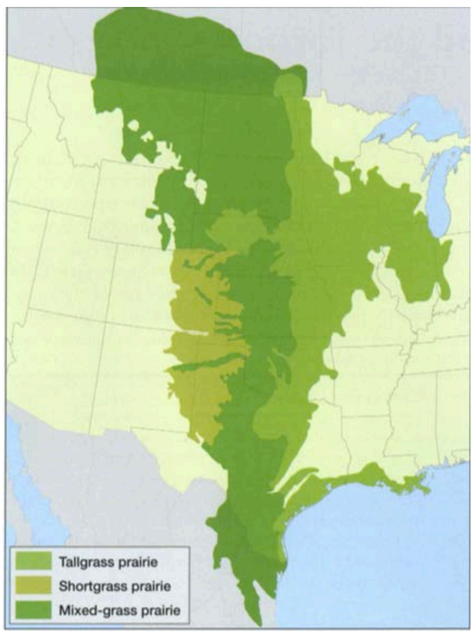

Fig. 1. The orignial extent of native prairie within the Midwest. From DeLuca and Zabinski 2011

Starting in 1820, the United States government passed several acts to encourage its citizens to expand westward. These acts, like the Homestead Act of 1862, gave pioneers 160 acres of land for little to no initial cost under the condition that they would improve the land. To the majority of pioneers, improving was synonymous with farming. The rise of agriculture brought a new age of soil erosion, which destroyed native habitat, and rapidly released C into the atmosphere. During this short time period, 120 million ha of tall-, mixed-, and short grass prairie was plowed across the Great Plains (DeLuca and Zabinski 2011). Plowing the soil disrupted the aggregates and released much of the C that was stored in the top 20-30 cm of the soils. Plowing also left soils more exposed to wind and water erosion, which increased the conversion of surface C stocks to atmospheric CO_2. The initial plowing was not the only negative aspect of agriculture. Agriculture reduced the photosynthetic input of C into the soils, limited the ground cover of crops to a seasonal basis and lessened belowground biomass production (DeLuca and Zabinski 2011). Limited ground cover and reduction in belowground biomass left the soils more vulnerable to erosion (Polasky et al., 2011). Soil erosion leads to a release of C stocks into the atmosphere and reduces the soils ability to sequester and store C in the future (Sanford et al., 2012).

The Mollic Epipedon and Soil Classification of Carleton

Located along the oak savannah border of southeastern Minnesota, the soils of the Carleton campus are primarily classified as mollic Alfisols. Alfisols, defined by the U.S Soil Taxonomy as fertile soils with high base saturation and a clay enriched subsoil horizon, are characteristic to hardwood forests. Mollisols, on the other hand, are defined as fertile dark colored soils located within prairie landscapes. Since Carleton in on the prairie-forest boundary, the soils of campus are a mixture of litterfall from forest ecosystems and fine root turnover from grasslands (Stadler and Koester, 2014). These soils contain high amounts of clay and have a mollic epipedon, demonstrating characteristics of both Mollisols and Alfisols.

The mollic epipedon, a characteristic component of Mollisols, also occurs in Andisols, Vertisols, Entisols, Inceptisols, and Alfisols as a mollic subgroup (Veenstra and Burras, 2012). It forms as a result of underground decomposition of organic residues and is a source of concentrated C content within the soil. This is important in determining C sequestration. The thickness and high SOC content of the mollic epipedon shows that Mollisols have sequestered large amounts of C over long periods of time. Although through erosion, SOC decomposition, crop removal, and leaching, the damaging effects of agriculture has diminished the thick organic rich mollic epipedon of Mollisols (Bockheim, 2014).

Mollisols are the soil order that is most commonly associated with agriculture, with 25% of Mollisol area used for cropland (Veenstra and Burras 2012), they are especially susceptible to the effects of farming. With the beginning of bulk, large-scale row-crop agriculture in the 1850s, the increasing effects of agriculture and urbanization throughout the Midwest depleted many Mollisols to the point where they no longer contained a mollic epipedon. In fact, approximately 11 to 33% of soils with a mollic epipedon were no longer classified as a mollisol after just 50 years of farming (Veeestra and Burras 2012). The accumulation of thousands of years of C sequestration can be quickly depleted within a matter of 50 years.

Despite accelerated C depletion, restoring C stores within Mollisols is possible through altering land use management practices, which can increase the C sequestration capacity of the soil. The large and relatively rapid changes in SOC as a result of agriculture indicates that there is considerable potential to restore the rate of carbon sequestration in soil through management activities that will reverse the effects of cultivation on SOC pools (Post and Kwon, 2000). The capacity for re-sequestration is high; it is estimated that with improved land management soils can regain up to 75% of their original C stores (Lal and Bruce, 1999). As for land management improvements, there are many new methods of for restoring C within soil. A few prominent techniques include conservation tillage, prairie restoration and the use perennial grasses, cover crops to increase the return of organic residues into the soil; and various control measures to prevent soil losses from wind and soil erosion (Huggins et al., 1998).

Agricultural Best Land Management Strategies and their Application at Carleton

Soil and plant carbon (C) dynamics in urban settings are acknowledged to be different from those of forest or agricultural landscapes (Kaye et al., 2006). Though in many ways, the damage of campus soil is similar to the damage caused by agriculture. For example, the compaction that results from construction on campus soils is similar to the compaction that results from conventional tillage in agricultural soils (Stadler and Koester, 2014). Additionally, campus leaf removal has similar effects on the soil as agricultural crop removal (Stadler and Koester, 2014), and vegetation alterations, such as the transition from native prairie to either sod or agricultural crops **(**Qian et al., 2010) reduces SOC input in both campus and agricultural soils. Considering these similarities, we propose the best way for Carleton to increase the C sequestration potential of their soils is to adopt agricultural best land management practices and adjust them to fit the land management practices of campus (Table 1). Of the best land management (BLM) practices that have proven successful in agriculture, we predict some of these practices will be similarly effective on the Carleton campus. This section will examine how soil is damaged in agriculture, analyze specific agricultural practices that have been developed to counteract this damage, and finally explore ways in which these practices can be adapted to aide soil health and C sequestration at Carleton.

Table 1. Connecting agricultural techniques to the Carleton Campus.

Soil Problem	Agricultural Technique	Adaption of Technique to Carleton
Soil Disturbance	No-Till Farming	Stricter regulations for construction projects
Residue Removal	Cover Cropping	Limited leaf removal
Belowground Biomass	Native Prairie Restoration	New species of turf grass with longer roots

Soil Disturbance

A common issue with C loss and soil health on agricultural land is soil disturbance. Soil disturbance is the result of conventional tillage, which uses heavy machinery to swap the topsoil and subsoil in order to redistribute nutrients (de Rouw et al., 2010). This practice has several negative effects on soils. First the physical tillage destroys soil structure and aggregate formation (Lal, 1993). Aggregates play a key role in maintain soil C levels by reducing the soil's susceptibility to erosion (Lal 1998). Erosion leaves the soil exposed, and when soil is exposed, it oxidizes and releases SOC into the atmosphere (Lal, 1993). Conventional tillage also leaves soil bare outside of the growing season. Bare soil is more susceptible to wind and water erosion, which as stated above, plays a large role in C loss in soil (Lal 1998).

In order to combat the negative effect of conventional tillage, farmers have developed conservation tillage techniques, one specific technique is No-Till (NT) farming. NT leaves a litter layer of crop residue to permanently cover the soil surface throughout the year (de Rouw et al., 2010). This permanent mulch layer protects the soil surface by reducing wind and water erosion, which in turn improves water infiltration (DeLuca et al. 2011). Protecting the soil surface and improving water infiltration improves soil structure and increases soil organic matter (SOM) content (de Rouw et al. 2009). As the name implies, NT farming also involves no actual tillage of the soil. This allows for further development of soil structure, which reduces erosion and maintains C stocks.

On Carleton's campus, the damage done to soil through construction practices is similar to that done by conventional tillage on agricultural lands (Stadler and Koester, 2014). The ongoing construction projects on campus have several negative impacts on soil health. Construction activity has shown to reduce soil infiltration rates from 70 to 99 percent (Gregory et al., 2006). Since decreased infiltration rates increase runoff and flooding potential, reduced infiltration as a result of construction can significantly decrease C stores within the soil. Additionally, bulk density in construction zones (mean=1.56 g/cm3, 97.39 lb/ft3) prove to be significantly higher than undisturbed zones (mean=1.03 g/cm3, 64.30 lb/ft3) (Alberty et al., 1984).

Similar to how farmers adopted NT to limit soil disturbance, Carleton could modify campus construction regulations to lessen the impact of construction projects. Carleton already provides a set of guidelines for construction companies on what they can and cannot do on campus (Stadler and Koester, 2014). These design standards already attempt to limit soil disturbance caused by construction. They ban building on steep slopes to prevent erosion and prohibit the driving and parking of vehicles across lawns and fields in order to prevent excess compaction (Facilitles, 2014). Though these policies are not well enforced, due to the high volume of construction and limited capabilities of the facilities staff (Stadler and Koester, 2014). In order to increase campus soils' C sequestration ability, Carleton could increase the level of enforcement regarding construction practices to stop common soil disturbance issues like erosion and compaction.

Residue Removal

Another common issues in agricultural soils is decreased C input as a result of intensive cropping (Lal 2004). As discussed above, conventional farming practices involve leaving fields bare outside of growing season, which in a climate like Minnesota's is nearly two-thirds of the year. Not only does bare soil increase susceptibility to erosion, but crop removal also reduces the amount of C deposited into the soil.

One solution to mitigate the negative effects of crop removal is cover crops (Liu et al., 2005). Cover crops are planted to maintain a plot of land in the off season, compared to a cash crop which is planted in the growing to sell for a profit (Wilson et al., 1982). Cover crops have been shown to increase soil aggregate stability and total organic carbon (Wilson et al., 1982) as well as increase long-term SOC accumulation. The adoption of permanent land cover in agricultural lands in the northern United States and southern Canada has increased the C sequestration coefficient by .88 mg CO2 ha^{-1} yr^{-1}(Boehm et al., 2004). Overall, cover crops prove to be a successful method for increasing the SOC pool (Berzseny and Gyrffy, 1997; Fullen and Auerswald, 1998; Nilsson, 1998).

While crop residue does not apply to the Carleton campus, fallen leaves and other dead plant materials play a similar role on campus as do crops on agricultural land (Stadler and Koester, 2014). Litterfall is an important source of SOM, which in turn increases the amount of SOC (Schlesinger and Andrews 2000). Therefore retaining litterfall on campus lawns has great potential to increase C sequestration. At Carleton, the leaves that fall on campus lawns are mulched and spread out evenly. Mulching decreases litter matter surface area. This prevents the leaves from rotting and blocking sunlight input into the grass (Stadler and Koester, 2014). As a result the litterfall increases organic matter input into the soil. In many ways this reflects the benefits of agricultural cover cropping. One exception is the "Bald Spot". In areas where the campus relies on having "picture-esque" grass, facilities removes plant litter (Stadler and Koester, 2014). Carleton's litterfall management is an example of an agriculture C sequestration technique that has already been adopted to fit Carleton.

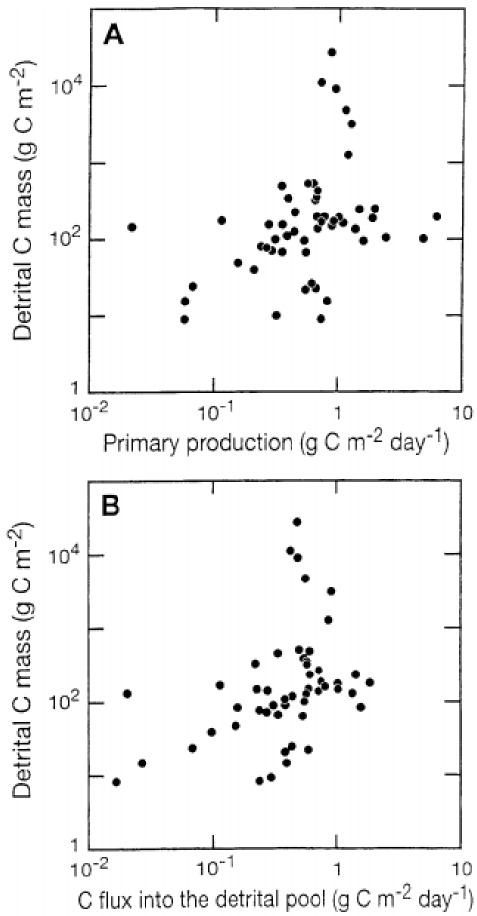

Fig. 2. Relationship between the mass of soil organic matter (gC/m2) and the net primary production (A) of litterfall deposition (B) in ecosystems of the world. From (Schlesinger and Andrews, 2000)

Belowground Biomass

A third common issue in agricultural soils is SOM loss by the conversion of native prairie to agriculture. It is widely known this transition has significantly depleted soil C (Hernandez 2013; Schlesinger et al. 1986; Lal et al. 1999). One method to remediate this depletion is native prairie restoration (NPR). Restoring cultivated land back to native prairie has the potential to reverse the C depletion that occurred in agriculture (Hernendez 2013; (Post and Kwon, 2000).

The potential for C sequestration through NPR depends on the amount of residue incorporated into the soil as well as the level of soil disturbance (Hernández et al., 20134). In order to maximize the amount of sequestered C within a restored prairie, it is important to minimize soil disturbances and maximize plant residue input. This can be done through increasing forage production (Conant et al., 2001). Forage production, such as grasses and legumes, replaces the shallow root systems of agricultural crops with dense root systems of native grasses. This increases belowground biomass production, which in turn leads to increased belowground C inputs and ultimately results in increased SOC (Conant et al., 2001).

Despite the potential of prairie restoration, it is not feasible on Carleton's campus for many reasons. The primary use of campus grassland is student enjoyment (Stadler and Koester, 2014). Students could not read on the Bald Spot or play soccer on Bell Field if it was grown out as a native prairie. In order to accommodate student use, facilities plants a Kentucky bluegrass (KBG) turf mix on campus green spaces (Stadler and Koester, 2014). KBG is a short meadow grass, predominantly used in athletic fields. While KBG has recreational benefits, its shallow and fine root system is not an effective C sink (Qian et. al 2008) and therefore it sequesters relatively low amounts of C. Below 10 cm, KBG stores only 20 g kg^{-1} of SOC (Qian et. al 2008). This number is far lower than the predicted potential of C sequestration for other types of turf and urban grass (Golubiewsk 2006).

While forage production as a part of NPR increases belowground biomass and increases SOC, Carleton could simulate the effects of forage production through replacing KBG with fine fescue (*F. arundinacea*). Fine fescue is a turf grass known for sequestering C deep into the soil profile (Qian et. al 2010). Fescue is in many ways comparable to KBG in terms of above ground features, meaning that the student use of campus green areas would not be compromised (Schultz, 2014). Fescue has dense root systems that extend deep into the soil profile. These deep roots promote soil stability, decrease soil erosion, and increase biomass input, all of which increase the C sequestration potential of the soil (Lal 2004; Qian et. al 2010). Compared to KBG, irrigated fescue inputs more C in the top 10 cm and also stores 28.3 g kg^{-1} of SOC below 10 cm (Qian et. al 2010). Additionally, the fescue root system is nearly twice as dense as KBG's (33.9 g kg^{-1} vs. 16.5 g kg^{-1}) (Qian et. al 2010). Fine fescue is an example of a land management strategy that holds high potential for increasing Carleton's C sequestration and limited negative externalities for the campus as a whole.

Counterpoints

While there are many effective techniques to increase the C sequestration potential of soils, is important not to view these techniques as stand alone actions. Optimal land use and land management requires joint consideration of the value of all objectives (Polasky et al. 2011). C sequestration is not the most important activity on Carleton's agenda. Many of the strategies presented above, like enforcing stricter construction standards or planting new turf on the athletic fields, could lead to serious increases in monetary costs. Beyond money, imposing new land management strategies also come with increased emissions of their own (Lee and Dodson, 1996). If our research found that agricultural land was more effective at sequestering carbon than native prairie, we still would not suggest turning the arboretum in farmland, because the C costs as well as habitat loss associated with that large of a change in land type would likely outweigh any possible benefits. Each ecosystem is individual and there will not be a silver bullet C sequestration technique.

Additionally, solving climate change is a complex equation in which C sequestration is just a small variable. While it has promising aspects, it is important to acknowledge that C sequestration is not the solution to global climate change. Today's carbon emission problems are not primarily a result of farming practices. Less than 8 % of United States' greenhouse-gas (GHG) emissions come from agricultural practices (DeLuca and Zabinski 2011). In comparison, 57% of emissions are released through burning fossil fuels (Agency, 2014). Also, the potential of SOC sequestration is finite in both magnitude and duration. Even the most effective C sequestration strategies have been shown to plateau after approximately a decade (Hernandez 2013). C sequestration is only a short-term strategy to mitigate anthropogenic enrichment of atmospheric CO_2. The maximum annual SOC sequestration potential is only 0.9F 0.3 Pg C/year. The atmospheric concentration of CO_2 at the observed rate of 1990 (3.2 Pg C/year) will continue to increase at the rate of 2.0–2.6 Pg C/year even with soil C sequestration (Lal, 2004). Given global increases in consumption, it is likely that the atmospheric concentration of CO_2 will continue to trend upwards. Thus, a long-term solution lies in developing alternatives methods of reducing atmospheric C. This is not to imply that studying C sequestration is not worthwhile, it just serves as a reminder that it cannot be the only focus in the fight against curbing C emissions and counteracting climate change.

Conclusions

Regardless of the method, Carbon sequestration rates are complex and affected by many factors, such as temperature, climate, and topography. Within the Mollisols and mollic Alfisols of the Carleton campus, C sequestration is often not a linear progression (Jelinski and Kucharik, 2009). Additionally much of soil research is limited to the last 50 years and, considering the time scale of soil formation, it is difficult to predict long term patterns of C sequestration based on these studies (Conant et al., 2001). SOC values have only been recorded within the last few decades, but damage as result of agricultural practices extends far further into the past than soil research. As a result we have no values for the original C storage levels in soils and therefore we cannot understand their full capacity for C sequestration. The combination of these elements makes it difficult to predict the C sequestration potential of Carleton's soil.

While paper bridges the gap between agricultural land management and urban land management, adopting agricultural techniques to specific situations, such as a rural college campus, is a relatively new realm of research. Not much research has been developed regarding C sequestration within urban soils. In order to continue improving C sequestration capacity of urban/anthropogenic soils, further research must be conducted on urban land management techniques.

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GEOL 258: Geology of Soils
11/3/14

The Potential for Carbon Sequestration in Riparian Zones: A Review for Carleton College

Abstract

In light of the global fears of elevated CO_2 in the atmosphere, carbon sequestration in soil has become an important sink for atmospheric carbon. Riparian zones are ecotones along the boundaries between the land and the water. These soils have an unmatched potential for sequestering carbon. Anoxic conditions brought on by inundation reduce soils capacity to degrade organic material and preserve carbon in the soil. Though riparian zones preserve more carbon, methane and nitrous oxides are often released from them at elevated levels compared to other soils. Methane and nitrous oxides are stronger greenhouse gases than carbon dioxide. Where possible, the salinization of wetlands offers another factor for wetland management, although research on salinization and carbon sequestration is minimal. Carleton College has riparian zones along the banks of the Cannon River and Spring Creek. Conscious management of these lands focusing on more frequent and prolonged inundation could increase the carbon sequestered on Carleton's property.

Introduction

Riparian zones are important ecological and physical zones in the landscape. These ecotones represent the transition between the land and the water (Gregory et al., 1991). Riparian zones can be adjacent to rivers, streams, tidewaters, lakes, reservoirs, ponds, and springs (Oakley et al., 1985). These areas are often geomorphically complex. Along rivers and streams, ancient scour is often filled with flood or alluvial deposits which form terraces, floodplains, banks, and areas in the channel (Swanson et al., 1982; Gregory et al., 1991). Therefore, riparian zones are often characterized by successive changes in environmental conditions across the ecotone; the influence of the river is most observed in the landscape directly adjacent and this influence decreases as you move away from the channel into the adjacent ecosystem. This gradation is visible in the biota observed while moving away from a river (Figure 1) (Oakley et al., 1985).

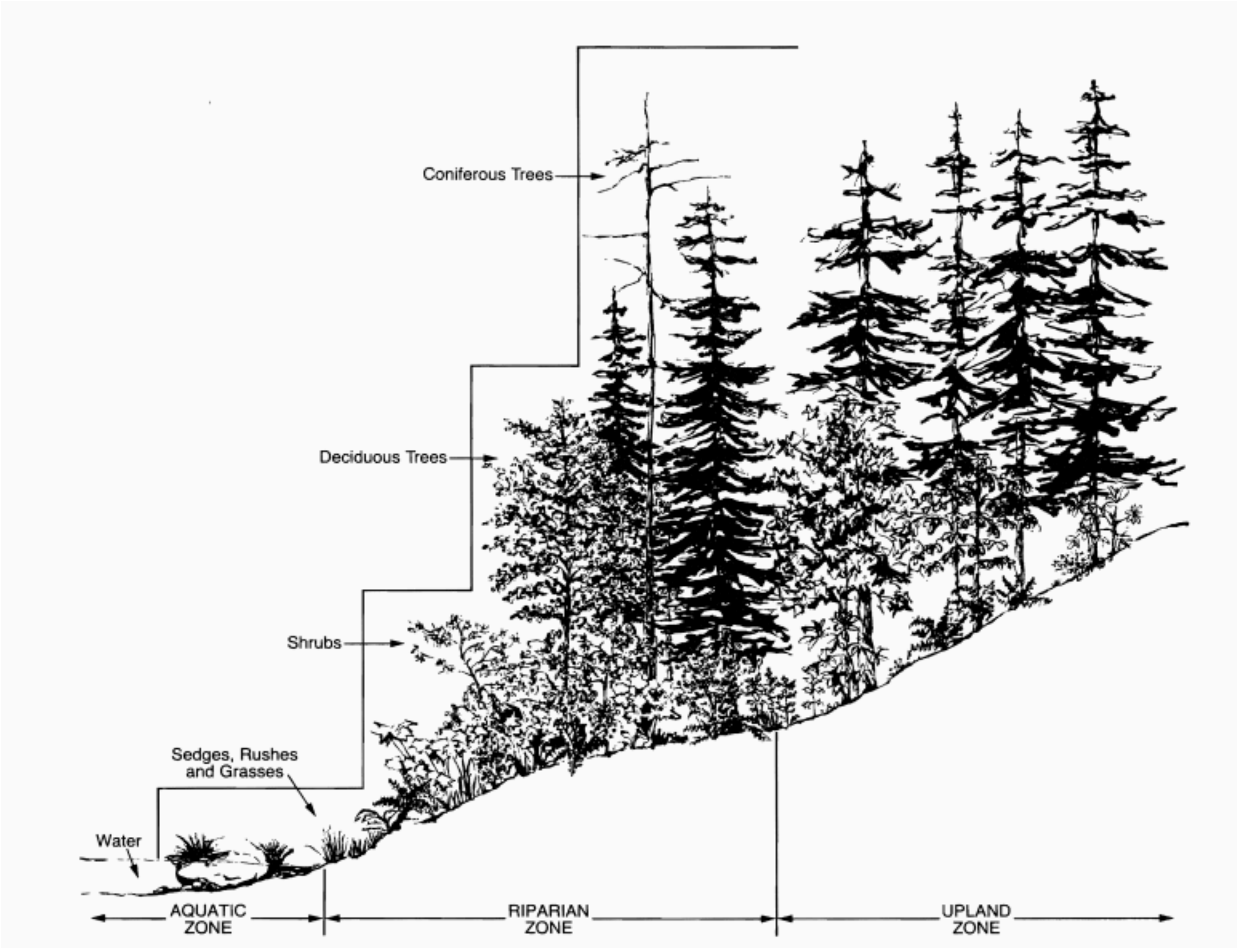

Figure 1. Within the riparian zone, the biota change up slope away from the river demonstrating how one of the soil forming factors changes drastically with distance from the river. This example is derived from a Pacific-Northwest setting and the figure is taken from Oakely et al. (1985).

Riparian zones are also characterized by the pathways through which nutrients and material move through these environments. Soils form in riparian zones primarily from two potential parent materials: alluvial deposits from upland areas (Gregory et al., 1991) and fluvial deposits from floods (Oakley et al., 1985; Gregory et al., 1991). Material is primarily removed from these environments at areas of bank erosion (Wolman, 1967). This demonstrates one of the dynamic ways that a riparian zone is a fluctuating, diffuse boundary.

Water movement through the soil exerts a large influence on nutrient movement in riparian soils. At the river's edge, one finds the contact between the subaerial stream and the subsurface water table. Moreover, the water table is relatively close to the surface in riparian soils and the soils may become inundated with water. Water moving through the soil can easily mobilize nutrients, including soil organic carbon (SOC) and transport them out of the ecosystem through by means of the river (Regnier et al., 2013). However, the frequent inundation of and the large presence of water in the soil can lead to an anoxic environment where decomposition of organic material is restricted (Schimel et al., 1994; Romero et al., 2005; Lennon and Nater, 2006; Polasky and Liu, 2006).

The potential for carbon sequestration in riparian zones is an important component of mitigating global warming. Carbon moves through the atmosphere, oceans, rock, and organic reservoirs. As atmospheric levels of CO_2 rise to levels not yet experienced by humanity, soils can be part of the solution to mitigation and act as a reservoir for carbon (Lal, 2004). Riparian zones have the highest potential for carbon sequestration due to their largely anoxic conditions where carbon remains immobile in undecomposed organics (Mitsch et al., 2013; Cerón-Bretón, 2014). The management of these lands is therefore incredibly important for local sequestration of carbon.

On Carleton's campus, these riparian zones are adjacent the Cannon River and Spring Creek. Soil maps show that these areas are mapped as specific soil series whose characteristics are dominated by the stream-land interface. For Carleton to improve the amount of carbon sequestration on campus, the management of the riparian zone must be an important component of the plan.

Floodplain Soils

Floodplain soils represent a very specific kind of soil. Like other wetlands, floodplain soils are areas of deposition (Downing et al., 2008: Ritchie and McCarty, 2008). In non-riparian flooded soils, deposition can come from airborne particles, material transported through the watershed, or created in the water (Downing et al., 2008). Other inputs to the system can be colluvial deposits from the surrounding areas.

The river exerts the greatest influence on floodplain soil composition. These soils are primarily the product of flood outwash accumulation from material transported through the watershed (Asselman and Middelkoop, 1995; Walling and He, 1997). Following Hjustrom's diagram, sands are deposited directly over the riverbank as flow velocities rapidly decrease (Figure 2) (James, 1985). Silts and smaller particles are deposited further away, creating a gradient of soil texture away from the river. These materials gradually accumulate through successive flooding events, when suspended material drops out of the overbanked water as velocity slows. While accumulation rates do vary, fallout Cesium-137 can be used to measure accumulation rates of soils in the floodplain (Ritchie and McHenry, 1990; Walling and He, 1997) As Cesium-137 has only been in the atmosphere since the 1960s, all soil containing this isotope should have been deposited after 1960. However, the floodplain may become inundated for longer periods of time following floods should outwash not drain, resulting in different patterns of deposition dominating the environment (Asselman and Middelkoop, 1995).

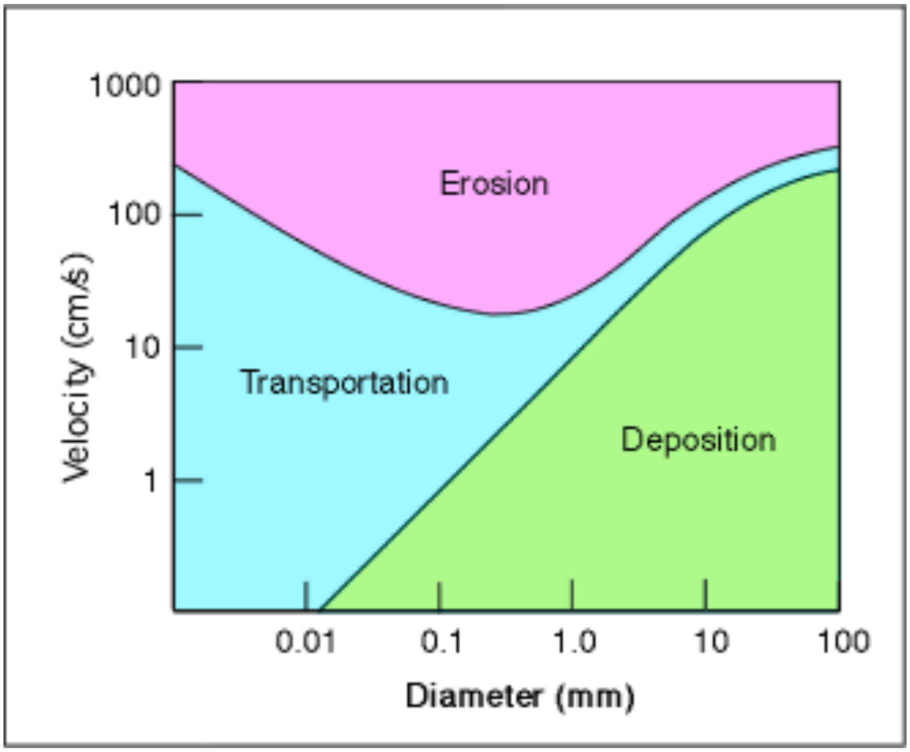

Figure 2. Hjulstrom's diagram. As water velocity decreases, particles transition from a being in suspension to being deposited. Larger particles can be deposited at faster velocities, while slower velocities are required to deposit smaller particles. Taken from DiVenere (2013).

Inundated Soils and Anaerobic Environments

When land is inundated with water, the natural decomposition processes of organic material are halted. When inundated or flooded with water, soils generally become anaerobic, meaning that there is little to no oxygen present. Without the presence of oxygen, processes that release carbon are severely muted. Inundated and seasonally inundated lands have the most potential for organic matter preservation and carbon storage due to low rates of organic matter decomposition in anaerobic environments (Polasky and Liu, 2006). It is important to note than when once inundated soils are drained, the anaerobic soils become exposed to the air. At this time, increased rates of aerobic decomposition occur, causing the carbon that was once locked in the flooded soil to be released back into the atmosphere most commonly as carbon dioxide (Trulio et al., 2007). In these cases, decomposition rates increase, to where 40% of metabolic litter can be decomposed in less than a few years (Schimel et al., 1994). Moreover, the rate of decomposition is considered more important to carbon sequestration in soils than the rate of input (Cerón-Bretón et al., 2014). Hence, soils with lower decomposition rates, such as wetlands, are more likely to have elevated SOC levels even if they do not have a high level of carbon input (Lennon and Nater, 2006).

When a flood occurs the carbon content of floodplain soils is altered in many ways. In agricultural settings, SOC is shown to be higher in areas of deposition and relatively lower in areas of erosion (Ritchie and McCarty, 2008; Wang et al., 2013). At depositional areas, soil is continuously being buried, storing more organic carbon (Ritchie and McCarty, 2008). The amount of dissolved organic carbon (DOC) in the soil decreases as water passing through the soil carries a portion of it away, resulting in less carbon being sequestered (Derx et al., 2014). A study of riparian zones on Chongming Island, China by Wang et al. (2013) demonstrate that DOC only accounts for approximately 5% of total SOC in riparian soils.

The amount of carbon in riparian soils may also fluctuate significantly between sites. SOC is directly related to the clay content in soil. This is because clay particles provide a reactive surface to which carbon can adhere (Schimel et al., 1994). This means that sandier floodplain soils may contain less carbon than clay-rich soils, even though organic matter is being buried. Time also has an influence on how much carbon is stored in wetland soils. While most soils have decreasing rates of carbon sequestration and saturate, wetlands can continually sequester carbon at a relatively constant rate (Polasky and Liu, 2006).

Carbon sequestration is dependent upon continual inundation of the soil. Thus in order for wetland restoration and the artificial creation of inundated zones to achieve maximum carbon sequestration the soils must remain inundated, or the carbon that was intentionally sequestered will be lost to the atmosphere once again. Results from a study in southern Quebec, Canada showed that alluvial soils subject to frequent flooding, defined here as a 0-20 year recurrence, on average were less rich in SOC and Soil Total Nitrogen (STN) as compared to soil plots outside of the flooding zone (Saint-Laurent et al., 2014). The average rates obtained for surface horizons, defined as 0-20 centimeters in depth, range from 2.0 ± 1.1% to 4.0 ± 4.1% (SOC) and from 0.2 ± 0.1% to 0.3 ± 0.2% (STN) for soils that were frequently flooded and those that were not, called non flood zones (NFz). The reason for the differences in SOC and STC in this study were attributed to a lack or near lack of litter material in the flooding zones, resulting in an overall lower rate of carbon input, resulting in a progressively lower SOC content for the soil.

Other soil properties both influence the capacity for carbon sequestration and are affected by riparian zone water fluctuations. Among these other variables are vegetation, geomorphology, C:N ratio, climate, salinity, pH, and temperature (Romero et al., 2005). With this in mind, had these flood zones been continually inundated, as opposed to becoming inundated and drying out up to 20 times per year, the paper would likely have told a different story. This is because the SOC decomposition rate would be lowered due to the soils continued inundation, and SOC decomposition rate is more important to the overall SOC content of a series than SOC accumulation (Cerón-Bretón et al., 2014).

Nitrogen Cycling and Methane Creation

Anaerobic respiration is responsible for altering levels of nitrogen in the soil as well. Similarly to carbon, nitrogen moves through the soil and atmosphere, aided by biotic and abiotic forces (Figure 3). Since oxygen is absent, microbes instead turn to reducing nitrogen into energy instead of the preferred carbon in a process called denitrification. Denitrification results in the release of nitrogen gas and nitrous oxide. Though denitrification results in the production of primarily nitrogen based gasses, it is limited by soil moisture, carbon content, and nitrogen content (Waters et al., 2014). Floodplains and wetlands are places of elevated inundation, which leads to increased denitrification (Orr et al., 2007). The nitrous oxides that are released through denitrification are also greenhouse gases, countering the positive effects of stored carbon in the soil (Prabha et al., 2013). The release of these nitrogen-bearing greenhouse gases is elevated where inputs of nitrogen into the soils are higher, such as in soils near agricultural land (Li et al., 2014). However, riparian wetlands have been studied and proven to be effective sinks for NO_3^-, capturing much of the nitrogen and minimizing the amount deposited downstream (Harrison et al., 2011). The denitrification process is a preferred sink because instead of temporarily immobilizing the NO_3, it removes it completely (Waters et al., 2014).

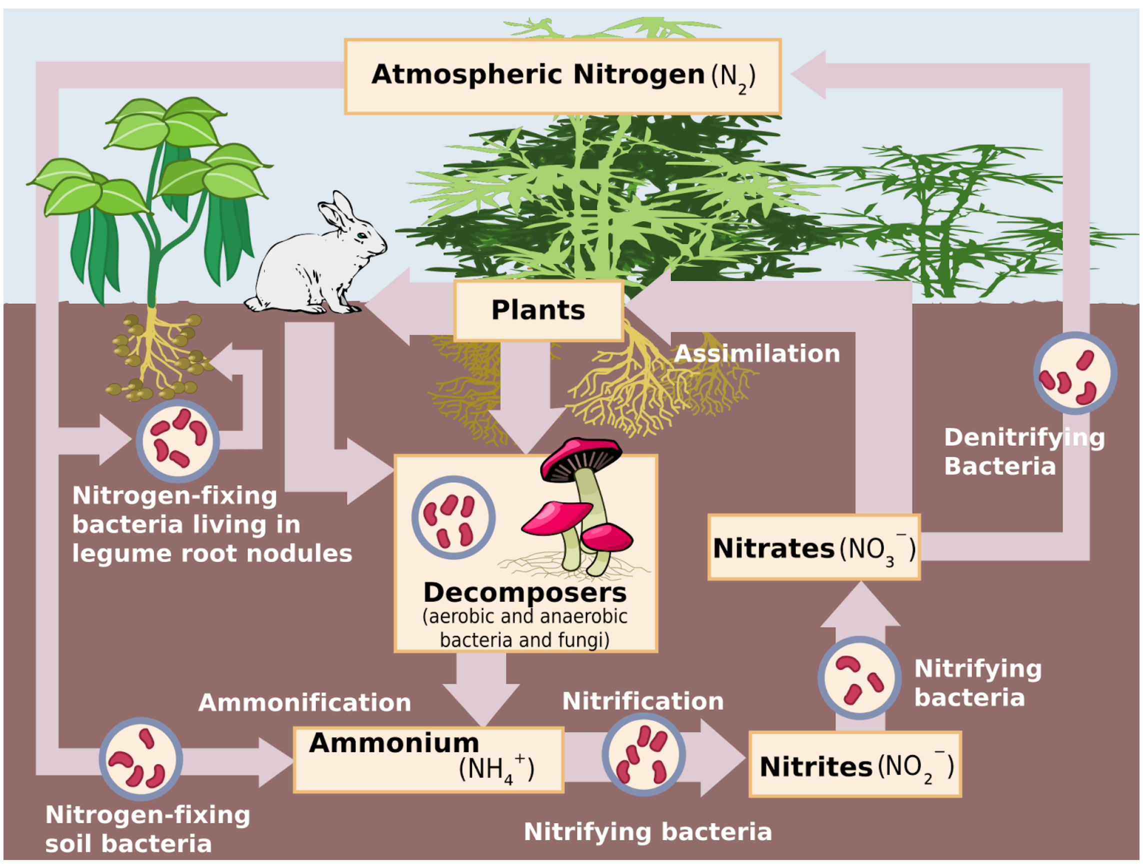

Figure 3. The Nitrogen Cycle. A model of the nitrogen moving through soil systems. While decomposers require oxygen to break down organic nitrogen into ammonia, denitrifying bacteria require anaerobic environments in order to break down nitrates. Taken from Wiki Commons.

In addition to releasing elevated levels of nitrogen gasses into the atmosphere, methane is also produced in riparian zones. Inundated lands have been shown to produce a disproportionate amount of methane (Lennon and Nater, 2006). The same low oxygen environments that promote carbon sequestration also favor the release of methane, a less common but more potent greenhouse as compared to carbon dioxide. The primary method in which methane is produced is through the reduction of CO_2 with H_2 (Bhullar et al., 2013). The gas is generated under anoxic conditions by methanogenic microbes that use CO2 as an electron acceptor (Mitsch and Gosselink, 2007). The amount of methane that reaches the surface is affected by abiotic conditions like temperature, pH of the soil, and the water table, i.e. inundation (Bhullar et al., 2013). For example, one study found that methane emissions were up to twelve times higher in inundated sites than CH_4 emissions in sites where the water table was just five centimeters below the surface in arctic Alaska (Morrissey and Livingston, 1992). Similarly, one study on the influence of temperature and water table position on methane production found a negative logarithmic relationship between methane emissions and water table depth (Moore and Dalva, 1993). Methane production fluxes in intermittently inundated hydric soils were significantly lower than the fluxes in hydric soils that were inundated continuously (Altor and Mitsch, 2008). So despite soil inundation resulting in lower levels of CO_2 emission into the atmosphere, that carbon sink is counteracted by inundated soils like riparian zones and freshwater wetlands emitting higher levels of methane, which can absorb twenty-one times more radiation than its more abundant counterpart CO_2 (Mitsch and Gosselink, 1986).

Saline Wetlands

While soils inundated with freshwater release methane in place of carbon dioxide, studies on tidal salt marshes indicate that they release a "negligible amount of greenhouses gases and store much more carbon per unit area," (Chmura et al. 2003). Thus the benefits of carbon sequestration in saltwater marshes is high, and, in comparison to freshwater marshes, the benefits are not offset by methane production (Trulio et al., 2007). This decreased methane production is caused by an increase in soil salinity. When data from Bartlett. et al is combined with "other tidal marsh studies", methane emissions to the atmosphere show a strong negative correlation with the long term average soil salinity in a marsh with waters ranging from what is essentially freshwater to 26 ppt (Bartlett et al., 1987). In addition, salt marshes do not become saturated with carbon over time, allowing them to sequester carbon for much longer without collapsing (Crooks et al., 2011). As salt marshes continue accretion they begin subsiding under their own weight, squeezing out water and increasing the density of the system, allowing for continual accretion at surface level, increasing the amount of carbon stored within (Crooks et al., 2011).

Despite this, conversion of freshwater marshes or wetlands to a more saline state has been studied relatively little as compared to carbon sequestration as a whole. The small amount of literature that there is is primarily focused on the vegetative changes that ensue when salinity is increased. As one might expect, increasing salinity in freshwater marshes results in several species of plant dying off (PIANC, 1993). If the rate of increased salinity is slow enough, salt-tolerant species are able to take their place (PIANC, 1993). When the salinity increases too rapidly, however, the marsh begins to erode due to the interval between the root mat of the freshwater plants decomposing and the roots of salt-tolerant vegetation taking root (PIANC, 1993). Seeing as an increase in salinity affects fish, vegetation, bottom organisms, and wildlife (PIANC, 1993) in varying ways it is impossible to predict whether or not increased salinity in a marsh is overall beneficial to carbon sequestration based on the literature available. The relationship between the increase or decrease of non-methane carbon sequestration rate versus the overall decrease in methane production caused by increased wetland salinity may be a topic worth investigating in the future, especially given the importance of carbon in general as of late. As of now, converting freshwater wetlands to saltwater wetlands is largely not understood and should be researched more before implemented.

Remediation

Given that carbon storage is higher in wet soils, the restoration of floodplain soils has become a priority. A study by Derx et al. (2014) shows that DOC in groundwater was higher when floodplain lands were restored. In this study, "restored" refers to a shallowing of the riverbank and a widening of the channel. In this model, DOC in shallow aquifers increases, which may be a net positive for carbon storage, but is detrimental to the safety of drinking water. Moreover, restored floodplains can be shown to operate relatively consistently with virgin floodplains, in terms of biogeochemical pathways. Restored floodplains have comparable rates of denitrification compared to unaltered floodplains (Orr et al., 2007). While this has not been shown for carbon sequestration, this data indicates that carbon sequestration may occur at levels comparable to virgin floodplains in restored areas (Orr et al., 2007). It is also important to note that the study drew conclusions using comparable rates of denitrification as opposed to levels of nitrogen in the soil.

Restoring native wetlands in the northern great plains as been the area of some study since the idea of sequestering carbon as a solution to climate change came about. Wetlands are a great potential sink of carbon and nitrogen (Olness et al., 2003; Erwin, 2009). A study of 205 wetland sites throughout the prairie pothole region found that native and semipermanent wetlands contained 4.1-5.0% carbon in the upper fifteen centimeters of soil. Cultivated wetlands (drained and undrained) and wetlands restored less than five years ago had on average 1.0 to

1.5% less carbon and 0.08 to 0.12 less total nitrate than soils in native wetlands (Olness et al., 2003). Additionally, the same study found that soils in restored semipermanent wetlands steadily increase their carbon and nitrogen concentration with age, and appear to reach pre-tillage levels within twenty years (Olness et al., 2003). Seasonal wetlands in the Olness study did not show the same responsiveness to restoration.

The number of studies that show that wetland restoration is a viable and effective method of carbon sequestration is convincing. While wetlands comprise 6% of the global soils, 12% of sequestered carbon in soils is in these areas (Erwin, 2009). Creating and restoring more riparian soils will only elevate the levels of carbon in soils. While cultivation has been suggested as the leading cause of soil carbon loss (Lal et al., 2004), restoration of area hydrology is not to be overlooked. This often takes the form of plugging drains, initial artificial irrigation, or moving dikes that prevent areas from flooding (Erwin, 2009). In addition to the high volume of work wetland restoration seems to entail, it is also costly. Developing a plan for carbon sequestration in coastal and delta wetlands cost an estimated $200,000 fin and of itself or the state of California, and that doesn't include any costs of restoration at all (Small, 2013). Conversion from freshwater to saltwater, though not much studied, could be too costly to even implement (PIANC, 1993). Salinization is not a practical, or even possible, management solution for Carleton's riparian soils.

Carleton's Floodplain

Carleton College's campus is quite familiar with flooding, in the past 5 years alone there have been two floods significant enough to warrant the mayor of Northfield declaring a state of emergency. Naturally, Carleton's campus contains several soils that become inundated or are likely to become inundated over the course of the year, and they are an important sink in terms of sediment and carbon flux in fluvial systems. There are several floodplain soil series that have great potential for sequestering carbon. The Colo series with a 0 to 2% slope, polygon 98, makes up one of the largest polygons on the soils map **(**Figure 4**)** and is only occasionally flooded. The Colo series mapped on Carleton's campus is generally poorly drained, with a parent material of alluvium and an A horizon depth of over 80 inches, and has a high available water storage capacity. Given these characteristics, the Colo series would be an excellent place to sequester carbon.

Though the Hamal loam (polygon 414) takes up only 0.6 acres in northeastern Rice county, it would still make an excellent place to flood and attempt to sequester Carbon. It is poorly drained and has a shallow slope of only 1 to 3 percent, and has a high available water storage capacity. The parent material is alluvium or colluvium over till and forms on moraines, so though technically not a floodplain soil though the series would function similarly in this situation, due to its poorly drained nature and shallow slope. The sand content is consistently low throughout the horizons, indicating that it would be good for inundating water. Though the profile contains layers other than A, the depth to the C horizon is over 50 inches. The Nerwoods loam series (polygon 757) is similar to the Hamal loam in that it is somewhat poorly drained, has a high available water storage capacity, and a large depth to the C horizon. However, the slope of 2 to 6 percent does not indicate that it is ideal of inundating water, though it certainly would be capable of doing so. This soil is also located several miles from the Cannon River, so this would be converted to a wetland.

The Rushriver fine sandy loam series (polygon 1360) would be an adequate choice for inundation. The Rushriver series has a parent material of alluvium and forms in swales and flats on floodplains. The series has a slope of only 0-1%, has an A horizon depth of roughly 40 inches, and is poorly drained, all characteristics that are good for an inundated soil. Though the Rushriver itself seems ideal for inundation, considering the soil is already frequently flooded it may not be a good choice for intentional inundation. In addition, the Rushriver has a somewhat high sand content and only a moderate available water storage capacity, which means it may not be ideal but would still inundate water well.

The Ankeny soil series (polygon 44) would sequester carbon somewhat efficiently based on it's 0 to 3% slope and high available water storage capacity. However, the Ankeny is well drained and has an A horizon depth of only 27 inches in Rice County, and contains a considerable amount of sand which is not conducive to storing water. It's location near the Cannon suggests that though it is not flooded periodically, it has been in the past which may indicate some usefulness in terms of carbon sequestration. Overall this would be the least preferable that is defined as a flood plain soil.

Though not a floodplain soil nor a soil series that could act as such, the Urban-land Estherville complex does cover the majority of campus so it is important to discuss. The complex forms on a slope of one to six percent, slightly larger than what has been seen in soils that are ideal for water inundation. In addition the series is largely sand, with lower horizons composed of very gravelly coarse sand, which is not conducive to water inundation. Finally, the series is defined as somewhat excessively drained and has a low available water storage capacity. It is clear to see that the majority soil on campus is extremely ill suited for water inundation and Carbon sequestration in general.

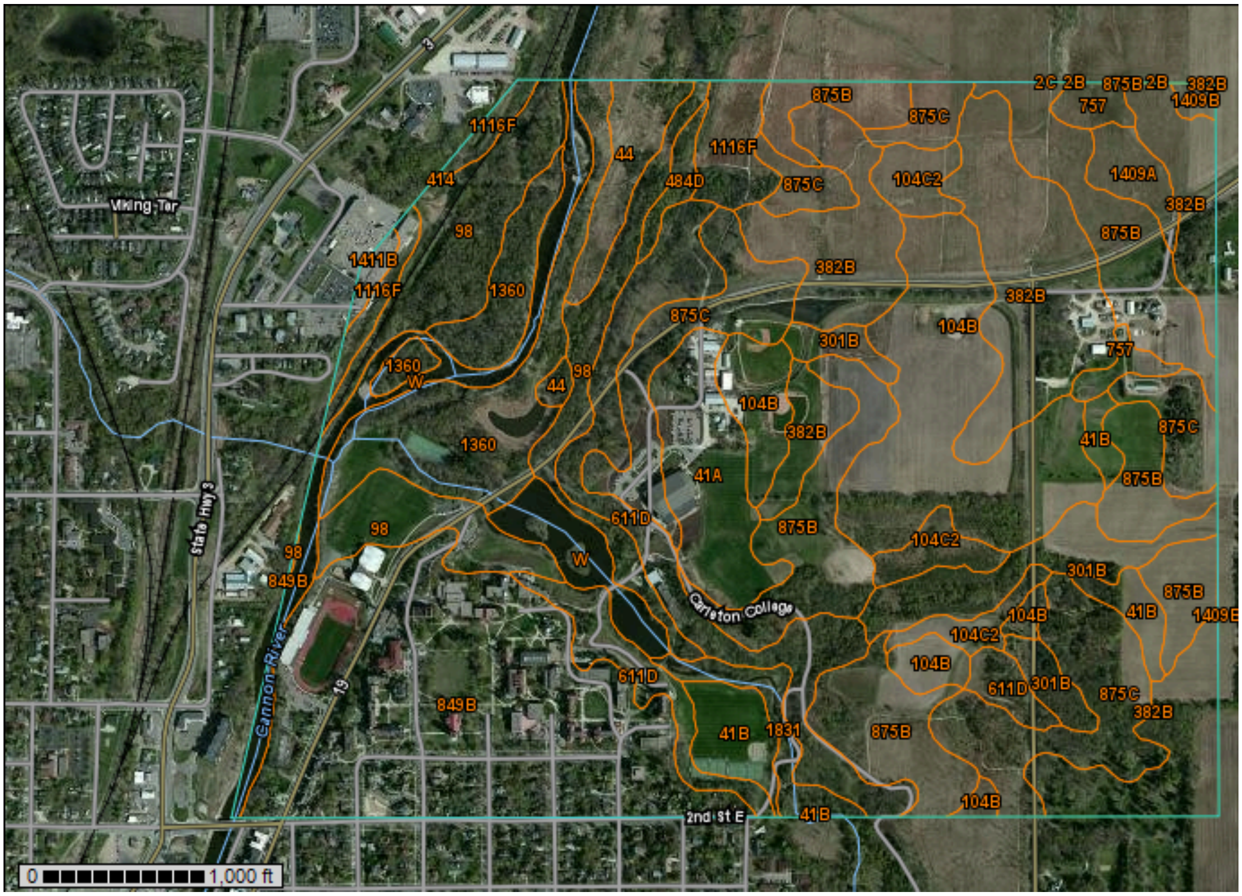

Figure 4. Soils map of Carleton College. The riparian zone soils noted by 98, 414, 1360, and 44 are found around the Cannon River which runs roughly SSW-NNE at this location and spring Creek, which flows into Lyman Lakes (at the center of the figure). This figure was made using the Web Soil Survey Tool available from the USDA website.

Conclusions

Carbon sequestration provides an effective if complex solution to the problem that humanity has created with carbon dioxide and other greenhouse gasses. Riparian zones, areas near water with parent material of sediment, are the most effective locations for carbon sequestration due to the inundated nature of their soils. Inundated soils cause anaerobic environments, reducing a soils capacity to degrade organic carbon. Since rate of decomposition plays a larger role in total soil carbon than rate of accumulation, we believe looking towards sequestering carbon in wet soils like riparian zones and wetlands is crucial to Carleton's climate action plan. Continually inundated soils can store more carbon for longer, as compared to occasionally or rarely flooded soils. Though wetlands and other inundated soils produce lower volumes of CO_2, some of this is counteracted by the production of additional nitrogen gases like N_2O through denitrification, where microbes turn to nitrogen for energy. In addition to nitrogen gases, inundated soils produce a disproportionate amount of methane. Saline wetlands, however, produce significantly less methane than freshwater wetlands do due to the increased salinity of the inundating water, and there is virtually no limit on the carbon that can be stored in saline wetlands. Unfortunately little research has been done on converting freshwater wetlands to saline wetlands. The results of those few studies discuss only the death and replacement of saline intolerant plant species, and leave the question of carbon sequestration open. Conversion of Carleton's wetlands to saline wetlands may increase carbon sequestration, though more research should be done before implementing such a change.

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Carbon source or sink? The influence of erosion on soil carbon cycling

Abstract

Recent concern for climate change has focused attention on the rising levels of atmospheric CO_2. As amateur soil scientists, we are interested in the intersection between soil erosion and carbon sequestration. For this paper, we reviewed literature covering the forces and mechanisms behind erosion, the various ways in which erosion can ultimately serve as both a source and a sink of soil organic carbon (SOC), and the complex factors surrounding the issue of erosion and the fate of the eroded SOC. We did not seek to definitively state whether erosion is largely a source or a sink; rather, we chose to review the processes that eroded soil go through and how variations within these steps can determine the SOC's eventual fate. These processes include the agent of erosion, the soil's properties, local climatological conditions, and topography. We will also briefly discuss how erosion affects Carleton's campus and what is being done to minimize its effects.

Introduction

The earth's soil system is a crossroads between atmospheric and terrestrial carbon pools. In light of the atmosphere's rising concentration of CO_2, soil scientists are increasingly interested in the movement of carbon between earth's soil system and atmosphere, for example through mineralization (a release of carbon to the atmosphere) and plant growth (Berhe et al., 2006; Ritchie et al., 2007). The process of erosion may accelerate or decelerate both of these processes. Furthermore, erosion is widespread across the globe—more than 60 percent of Earth's land is at a slope that is greater than 8 percent, which makes it vulnerable to erosion (Berhe et al., 2006).

Amplified by a projected acceleration in the hydrologic cycle, erosion will be an important factor in future carbon cycling.

However, the impact of erosion upon SOC at both landscape and global scales is unclear. Although studies of erosional sites have recorded net losses of SOC because of physical movement and degradation of plant communities, studies of entire landscapes have recorded both losses and gains (Van Oost et al., 2012; Park et al., 2014; Wiaux et al., 2014; Berhe and Kleber, 2013). On the one hand, erosion may disrupt aggregates and expose once-protected SOC to soil microbes, thereby accelerating respiration. On the other hand, the decrease of SOC at an eroding site may increase the site's potential to sequester more carbon. What's more, eroded SOC may be buried, and therefore protected, by repeated deposition.

The process

Erosion is often divided into three phases: detachment, transport, and deposition. The net loss or gain of SOC during erosion depends on the rate of carbon sequestration and mineralization at each of these phases. At the site of detachment, erosion may harm primary productivity, which is the ability of plants to grow and sequester atmospheric carbon; during transport, erosion may lead to physical and chemical breakdown of soils, for instance by mineralization; And at the site of deposition, SOC may be buried in a low-mineralization environment, where mineralization is reduced (Van Oost et al., 2012).

Variations within each of these phases are determined by myriad landscape and soil properties. The different agents of erosion—wind versus water—each have different effects on soil particles. Unique topographies shape the transport of soil. The physical and chemical soil properties also determine a soil's susceptibility to erosion and mineralization. Additionally, soil moisture content supports both soil structure and microbial activity, leading to complicated interactions with the SOC. In sum, the process of erosion comprises multiple, variable stages, which have implications for the movement of SOC.

Erosion at Carleton

Soil erosion is a large concern for Carleton College, both on campus and in the Cowling Arboretum. Within the main campus, pedestrian traffic is the main agent of erosion. When the paths become too congested, pedestrians stray from the paved paths and overflow onto the lawns. This kills the vegetation, which leaves strips of unprotected soil that are more susceptible to further erosion via water and wind, thus greatly accelerating erosion in that area over time. Some areas on campus are completely devoid of grass due to foot traffic; the possibility of severe erosion in those areas is a concern both for aesthetic and safety-related purposes. Soil is also left exposed during campus construction projects, which are common during the summer. Within Cowling Arboretum, trail erosion has become so problematic that trails have had to be closed and relocated in the past. This is largely because older trails were covered with gravel, which would be swept away by water during flood events (Braker). These instances of erosion at Carleton likely have a large impact on the campus's carbon storage potential.

In the following sections, we outline some of the factors that determine whether erosion is a net source or sink of carbon, based on results from recent studies. We also attempt to extend these patterns to Carleton's campus.

Agents of erosion

Soil erosion is influenced by both natural and anthropogenic processes. Pimentel et al. (1995) state that 75 billion metric tons of soil are removed from the land annually via water and wind erosion; most of this erosion occurs on agricultural plots, where the natural landscape has been drastically altered. Though soil erosion may be accelerated by human influences, the primary forces responsible for the three-step process of detachment, transport, and deposition are natural. Two of the main agents behind soil erosion are water and wind. It is important to understand some of the mechanics behind these two forces in order to better relate erosion to SOC transport, loss, and sequestration.

Water erosion

Soil is eroded differently depending on the agent behind the erosion. Water can erode soil in two different ways: through rainsplash energy and through runoff (Bryan, 2000). Soil erosion via the kinetic energy of falling raindrops works to break up soil aggregates, the first step of the erosional process. Rainsplash erosion is considered to be a selective process; the particles most susceptible to erosion will be mobilized first and their movement affects only the local area (Kirkels et al. 2014; Lal 2004). Of the different particle sizes comprising soil, clay is the most difficult difficult to erode because of its cohesivity—its tightly-bonded molecular structure means that it is difficult to break its bonds and get clay-size grains loose. Silt and fine sand are thus the primary particles within a soil affected by erosion. Additionally, SOC is low-density and is typically concentrated within the topmost layers of the soil, making it very susceptible to erosion (Kirkels et al., 2014).

Rainsplash erosion is dependent on several factors, including the heaviness of the rain, the surface characteristics of the soil, and the soil's properties. For example, an extreme rainfall would deliver a high amount of kinetic energy, thus breaking up larger aggregates than a light drizzle would. The breakup of these aggregates can lead to either in situ mineralization—a release of SOC to the atmosphere—or to the broken-up soil being swept away by runoff, the second mechanism of water erosion. Figure 1 describes the different paths that an aggregate broken by rainspash can take in the process of transportation and deposition. Mineralization is a possibility at each step of transportation, indicating that soil eroded by rainsplash can serve as a possible source of atmospheric carbon.

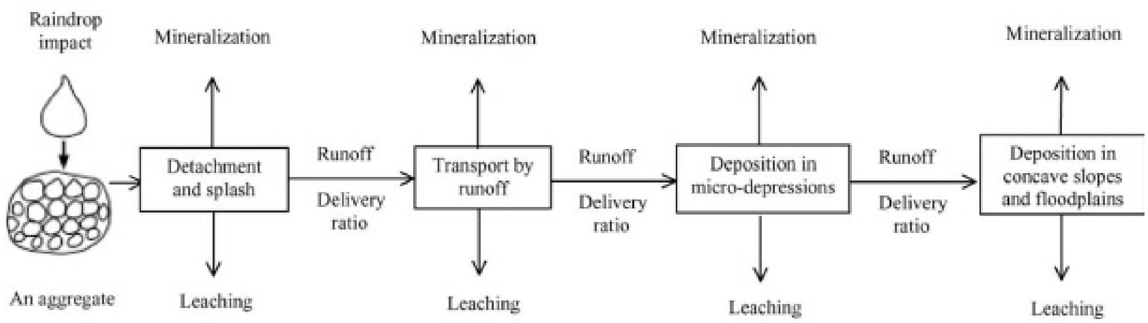

Fig. 1. The possible paths of an aggregate disrupted by rainsplash. Taken from Lal (2004).

Runoff affects broad areas and creates incised rills on the landscape, or channels for soil and water to run down. These channels can be thought of as small streams, and thus can be seen from a geomorphic angle. Flow discharge, stream power, and suspended bed load are all things to consider when determining the extent of soil erosion via runoff. Kirkels et al. (2014) see runoff as a nonselective type of erosion, as it is a large-scale process that can carry sediment into fluvial systems beyond the local environment. However, Lal (2004) argues that all types of erosion are selective processes that are dependent on particle size, not on the breadth of their reach.

Wind erosion

Wind erosion is especially prevalent in arid and semiarid areas (Wang et al., 2014b). Like water erosion, the severity of wind erosion is largely dependent on the soil's characteristics and atmospheric conditions. Unlike water erosion, where eroded sediment either joins the fluvial system or is pushed into a depression, material eroded by wind can end up deposited in wide-reaching areas. Óskarsson et al. (2004) postulate that wind-eroded materials are transported selectively based on size--the heavier mineral fraction is deposited relatively close to its original site, while the low-density organic matter is transported much farther beyond the local region.

Because erosion disrupts the natural cycles of SOC formation and transport, it cannot be immediately determined whether the eroded SOC will be sequestered or released to the atmosphere. Van Oost et al. (2009) estimate that only 20% of water-eroded material in the United States ends up as part of the river network—the remaining 80% must either undergo significant mineralization or become stored in catchments and depressions. Eroded SOC that is deposited in a depression becomes protected by the accumulation of material on top of it, decreasing its chances of mineralization and thus retaining the SOC within the soil (Lal 2004). Material that does not end up in a depressional area is subject to different influences that could lead to its mineralization. The potential mineralization of deposited organic matter is partially dependent on the decomposability of the materials within the soil, further complicating the possibilities for the future of the eroded material (Óskarsson et al., 2004).

Whether the soil is eroded by water or wind, it follows a similar basic pattern. Erosion results in the break-up of aggregates. The broken soil is then either easily transported and deposited, thus becoming a carbon sink, or becomes exposed to microbial processes and mineralizes (Lal, 2004). However, which path the eroded soil will take depends in part on the force behind the erosion—each mechanism goes through the three stages of erosion differently, thus impacting the eventual fate of the eroded SOC.

Soil properties and SOC

Soil properties such as texture, aggregation and porosity shape the flow of carbon through landscapes. At detachment sites, these properties determine soil's erodibility and its potential to support new plant growth. As soils move toward their final resting places, these properties determine the rates of mineralization. Finally, at depositional sites, these properties determine the rates of mineralization.

Detachment sites

It is important to understand the determinants of erodibility because highly eroded soils offer little support for plant communities. Thus, high rates of erosion may lead to a decrease in net primary productivity. Several studies have reported that certain particle fractions are correlated with erodibility. For example, Bonilla and Johnson (2012) reported a negative correlation between between silt content and erodibility. This result agrees with the results of Di Stefano and Ferro (2002), who found a sweet spot for erodibility in particle sizes between 20 and 200 micrometers, which include silt, fine and very fine sand. Above that range, particles were presumably too massive to move. Below, they were too cohesive (Di Stefano and Ferro, 2002, as cited in Amezketa, 1999). Indeed, several studies have suggested a negative correlation between erodibility and clay content. Amezketa (1999) reported that clayey soils had high aggregation, which has been found to decrease erodibility. Specifically, Amezketa (1999) found that soils with high concentrations of 2:1 clays had especially strong aggregates. Similarly, Young and Mutchler (1997) noted a correlation between soil aggregation and content of montmorillonite, a 2:1 clay. Several studies have found an additional correlation between clay content and infiltration, which has also been found to decrease erodibility. Capriel et al. (1995) studied associations between different soil fractions and types of soil organic matter (SOM), and found that clayey soils often contained high concentrations of carbohydrates and proteins, while sandy soils contained high concentrations of alkyl carbon. As a result of these chemical properties, sandy soils were more hydrophobic than clayey soils, which suggests that clayey soils have better infiltration than sandy soils. Zavala et al. (2014) reported a similar negative correlation between clay and water repellency. In addition to silt and clay content, the presence of large rock fragments may determine a soil's erodibility. More specifically, rock fragments have been found to mediate the forces of wind and water on soil's surface layers (Cerdan et al. 2010). Cerdan et al. (2010) reported lower erodibility in Mediterranean regions than in other European regions, despite greater slope gradients and rainfall at the Mediterranean sites. To explain these results, they noted the high content of rock fragments at these sites. Indeed, the rate of particle detachment due to slaking is known to decrease as rock cover increases, because rocks intercept raindrops before they hit the soil surface (Torri and Borselli, 2000).

Although erosion may hinder plant growth, it may also increase a detachment site's ability to retain sequestered carbon. Several models of SOC dynamics assume that a soil's carbon stock will grow proportionally with carbon input (Six et al., 2002). This implies that carbon stocks can increase indefinitely as long as carbon inputs also increase indefinitely. However, recent evidence suggests that SOC may reach a saturation point (Six et al. 2002, Tan et al. 2014, Wiaux et al. 2014). Some experiments have found, for instance, that SOC concentration stayed nearly constant, despite two- to three-fold increases in carbon inputs (Six et al. 2002). This implies that the removal of SOC at previously-saturated detachment sites may make room for a net increase in SOC.

Whether a soil is saturated depends on the extent of primary productivity (Van Oost et al., 2012), as well as certain soil properties. Much SOC is retained in soils because it is chemically bound to clay and silt particles (Six et al., 2002). Thus, soils with higher concentrations of clay and silt particles have the potential to retain more SOC before reaching saturation (Van Oost et al., 2012). More specifically, Six et al. (2002) found that 2:1 clays were better able than 1:1 clays to stabilize SOC. They also found improved stabilization in clays with high cation exchange capacities and large specific surfaces. A soil's pH may also affect its ability to stabilize SOC. Specifically, adsorption has been found to increase with soil acidity (Tan et al., 2014).

Transport

As soils move from detachment to deposition, they are susceptible to increased rates of mineralization. In part, this is because transport often leads to the breakdown of aggregates. Aggregates form physical barriers between microbes and SOC, and block the diffusion of oxygen, which microbes need. Indeed, improved aggregation has been found to reduce mineralization (Park et al., 2014). Under the assumption that erosion destroys all aggregation, aggregates that encapsulate more SOC upslope are more vulnerable to mineralization as they move downslope. Six et al. (2002) reported that macroaggregates (>250 micrometers) offered more physical protection than microaggregates. These results agree with the results of another experiment, in which both microaggregates and macroaggregates were crushed, to simulate erosion. In the macroaggregates, mineralization increased by 1 to 2 percent. In contrast, mineralization in the crushed microaggregates increased by three to four times (Six et al., 2002). This suggests that soils with smaller aggregates lose more SOC during transport than soils with larger aggregates.

But aggregation isn't the only protection for SOC. For example, SOC may bind to mineral surfaces, and these bonds are unaffected by transport. Also, SOC may be protected by biochemically-determined recalcitrance. Complex carbon molecules, such as lignin and polyphenols require several enzymatic steps to be broken down. Thus, these forms of carbon are relatively safe from microbial respiration, even when they're unprotected by aggregates (Van Oost et al., 2012).

Deposition

Soil properties in depositional sites are important because they influence the rate of mineralization. If mineralization is significantly stunted when soils reach deposition, erosion will move toward a net carbon sink. Several properties that stifle mineralization are common in depositional areas. For instance, footslopes are often characterized by high moisture, low oxygen and high compaction, which limit mineralization (Berhe et al., 2006; Berhe and Kleber, 2013). Because accumulation of SOC at depositional sites is likely limited by saturation, the low pH that is characteristic of wet soils also makes depositional sites good places for SOC accumulation, because acidity is associated with adsorption (Berhe and Kleber, 2013).

Another common feature in depositional sites is a high concentrations of SOC, because erosion preferentially carries small SOC fractions (Berhe and Kleber, 2013).

It's unclear how this affects the net movement of SOC in a landscape. Tan et al. (2014) found that as SOC accumulated, it mineralized more and humified less, causing a negative feedback loop of SOC accumulation. This phenomenon could have been caused by increasing pH, which accompanies SOM (Tan et al., 2014). As pH increases, adsorption to mineral surfaces has been found to decrease (Tan et al., 2014). Furthermore, in acid soils, increasing pH has been found to enhance microbial activity, thereby increasing mineralization (Tan et al., 2014). SOC is also associated with dark-colored soils, which absorb heat. Heat, in turn, increases the rate of respiration (Tan et al., 2014).

In contrast, Berhe et al. (2006) found that decomposition in a depositional site decreased with the addition of more eroded soil. Like Tan et al. (2014), they reasoned that erosion preferentially transports SOC particles. However, they further reasoned that most labile fractions have already mineralized once they are deposited. Thus, the SOC that reaches depositional sites is a poor substrate for soil microbes. By diluting the concentration of labile SOC, eroded SOC also dilutes the concentration of soil microbes, reducing the rate of decomposition (Berhe et al. 2006).

Although repeated deposition may shield deep layers of SOC from the atmosphere, certain soil structures may facilitate the movement of water and oxygen, which support microbial communities. For instance, shrink-swell soils, such as vertisols, include deep cracks that connect the subsurface to the atmosphere (Chaopricha and Marín-Spiotta, 2014).

Soil properties at Carleton

The Carleton campus is likely dominated by two soil series: Rushriver, a Mollic Fluvaquent, and Estherville, a Typic Hapludoll (USDA). Because Rushriver forms from floodplain alluvium, at low slope gradients, it is unlikely to be a source of eroded soil. Rather, we suggest that Rushriver is characteristic of depositional sites on Carleton's campus. The Rushriver series may be conducive to SOC storage because it is poorly drained (USDA). This presumably limits infiltration of oxygen into the soil, suppressing microbial activity (Berhe and Kleber, 2013). On the other hand, the Rushriver series is dominated by sand-size particles, which have less surface area than clay and silt particles, with which to form chemical bonds with SOC. This suggests that Carleton's depositional sites are characterized by low saturation points, and therefore low potential to store SOC (Six et al., 2002).

The Estherville series is found on slopes ranging from 0 to 70 percent (USDA), so it is likely the source of eroded soil that is deposited downslope. The series is dominated by sand-size particles, and it has a deep A horizon (USDA. These characteristics suggest that, under low rates of erosion, Estherville-dominated landscapes may be a net carbon sink. Because the series has a deep A horizon, much of the surface soil can, presumably, be removed before primary productivity is affected. As long as primary productivity is continual, SOC that is lost to erosion will eventually be replaced through plant roots (Berhe et al., 2006). In addition, the series' high concentration of sand particles suggests that it has a low SOC saturation point. Thus, removal of SOC by erosion may free up space for further SOC storage, by exposing mineral surfaces that had been previously unexposed to SOC (Six et al., 2002).

Soil temperature and moisture

Soil moisture levels and temperature are important factors that control the fate of SOC. Wiaux et al. (2014) found that both volumetric water content (VWC) and temperature of the soil are highly dependent on the soil's location on an eroding slope. They also found that VWC can affect the SOC in a number of ways, namely affecting soil respiration. For soil in dry conditions, moisture has a positive effect on soil respiration because microorganisms require moisture both for metabolic processes and to ease their access to the SOC pool. However, in wet conditions, additional moisture saturates the soil and prevents respiration (Wiaux et al., 2014).

The temperature sensitivity of SOC is shown to be highly dependent on moisture content, especially for colluvium accumulated at the base of an eroding slope (Wiaux et al.,, 2014). Additionally, Wang et al., (2014a) noted seasonal temperature variations and their effects on soil erosion, notably freeze-thaw patterns. Their findings suggest that as the water within soil freezes, fine particles bind together to form coarse grains, thus decreasing the highly erodible fraction of the soil. If frozen soil is less susceptible to erosion, then the mineralization of the SOC cannot occur. However, as temperatures rise, soil thaws from the top down. The thawed topsoil is shown to be increasingly susceptible to erosion because water cannot deeply permeate the soil; the water thus must run off and take topsoil with it. This eroded soil then joins other runoff sediments, where it is impossible to tell exactly what will happen to the SOC.

These findings regarding how temperature and moisture can affect soil respiration have hefty implications for eroded soil, particularly for the labile soil deposited in catchments and basins (Wiaux et al., 2014). The fate of the SOC within these pools is tied to the local temperature and moisture patterns. Wang et al. (2014a) state that soil with a high VWC is more readily eroded by freeze-thaw processes due to the increased freezing and binding of the soil particles. Additionally, temperature and moisture are found to vary throughout the landscape (Wiaux et al., 2014). Fig. 2 explores the relationship between moisture content, temperature, and respiration. The rate of CO_2 respiration is found to be highest when both soil moisture content and temperature are high (Wiaux et al., 2014). However, like other factors influencing the fate of SOC, temperature sensitivity and local climatological patterns vary geographically and it is difficult to draw universal conclusions.

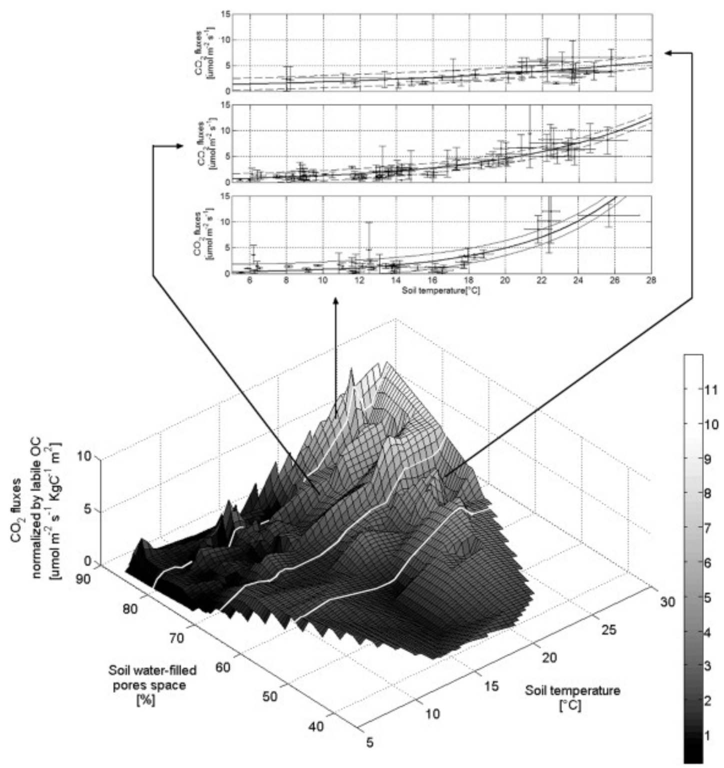

Fig. 2. The rate of CO_2 flux, or exchange, with the atmosphere is highest when both soil water content and temperature are high. Taken from Wiaux et al. (2014).

Beyond the localized patterns of temperature and moisture variation present in eroding slopes are regional climatological patterns. Climate can greatly affect SOC content, both during pedogenesis and after subsequent erosion and deposition; dry climates typically experience a greater degree of wind-induced erosion, whereas wetter climates are more subject to fluvial erosion (Chaopricha and Marin-Spiotta, 2014). In their analysis of Great Plains paleosols, Chaopricha and Marin-Spiotta (2014) found that deep, well-drained soils with low levels of moisture have less microbial activity, therefore leading to less mineralization of the SOC. Their findings are in line with those of Wiaux et al. (2014), who state that moisture is needed to promote microbial respiration. If eroded soil is deposited and then deeply buried, it is less likely for it to be sufficiently wet to undergo mineralization and gas exchange with the atmosphere (Chaopricha and Marin-Spiotta, 2014). However, whether the eroded material will be deeply buried hinges on the other factors outlined in this essay—the agent of erosion, the soil's properties, and the topography.

Carleton's climate

The soils at Carleton are highly susceptible to erosion due to the extremity in both temperature and moisture regimes. Carleton is located in a region that undergoes both extremely low temperatures and high degrees of rainfall throughout the year. Thus, the soils are subject to significant erosion via snowmelt runoff and freeze/thaw processes. Northfield also typically experiences period of heavy rainfall in the late spring and early summer, rather than a more spread-out precipitation pattern. These rainstorms can deposit as much as 5 inches of rain at once, which channelizes soils in barren areas and creates deep rifts—sometimes as deep as 15 inches (Braker). These climatological factors serve to accelerate erosion on Carleton's campus and must be taken into consideration when discussing the effects of erosion at Carleton.

Severity of erosion

An additional factor regarding the fate of eroded soil is the severity of the erosion. A study conducted by Battiston et al. (1987) measured the growth of corn on hillslopes exhibiting varying degrees of erosion. Plant growth is important to the topic of erosion because plant growth on eroded sites can indicate a replacement of the eroded SOC in that area—SOC can be dynamically replaced via plant growth at sites of previous erosion, serving as a sink of atmospheric carbon (Lal, 2004). Battiston et al. (1987) found that there was little to no impact on the yield of corn until about 50% of the original soil had been eroded away. This suggests a nonlinear relationship between soil erosion and plant growth. These results can be further extrapolated to discuss SOC on eroded hillslopes; if plant growth serves as a sink of SOC, erosion must be very severe in order to disrupt that natural process and begin releasing that carbon to the atmosphere. Soil erosion may only harm a soil's ability to dynamically replace SOC when a slope is severely eroded, rather than slightly eroded (Battiston et al., 1987).

Severity of erosion is important to consider not only because of how it can destabilize entire slopes, but also because of its impact on soil aggregates. Six et al. (2002) examined aggregate size in relation to SOC content and erosion. Soil aggregates act as protecting structures for the SOC they contain; however, the degree of protection varies with size. Macroaggregates (>250 μm) offer minimal protection, whereas microaggregates protect the SOC trapped within them from decomposition. Studies showed that the breakup of macroaggregates during erosional processes increased mineralization by only 1-2%. The crushing of microaggregates, however, increased mineralization 3-4 times that of the macroaggregates. These results point to the important role that microaggregates play in the scheme of erosion and C-sequestration. These small, dense aggregates are shown by Six et al. (2002) to have a greater potential for C-stabilization because they are more difficult to break up. This suggests that a severe degree of erosion would be needed in order to destabilize the SOC stored within microaggregates.

Berhe et al. (2006) examined how weather events can affect the severity of erosion. They cite the rate of erosion as a key factor in determining the portion of soil that will end up mineralized. Throughout erosion occurring at a non-accelerated pace, the labile fraction of the soil decomposes quickly, thus leading to the mineralization of the SOC. Heavy rainfalls, on the other hand, can channelize soils and lead to immense and rapid transfers of sediment downslope. Because the soil is being transported and deposited in such a relatively short span of time, the eroded SOC has a lesser chance of mineralization (Berhe et al., 2006). Channelization frequently occurs on Carleton's campus during periods of heavy rain. A future study for students to conduct could perhaps examine the change in SOM levels of the eroded material at the bottom of such a channel in the days following a rainstorm.

Topography

Topographic features such as slope, profile, curvature and aspect shape the movement of water and soil particles. Thus, topography influences the severity of erosion, which has consequences for primary productivity; the amount of time soil spends in transport, when mineralization is high; and the significance of deep burial.

Cesium-137: a revolutionary tool

As soil scientists have sought to correlate topographic features with soil movement, many have used a similar technique: measuring the distribution of 137Cs, a radioactive isotope, across various landscapes. The isotope was released into the atmosphere in the 1960s, as fallout from nuclear weapons tests, and distributed across surfaces by precipitation. It was quickly adsorbed by soil particles where it landed (Martz and de Jong, 1987). Because the initial distribution of 137Cs was, presumably, uniform across any particular landscape, researchers can recreate the movement of soils since the 1960s by measuring the relative distribution of 137Cs.

To relate the movement of carbon to the movement of soils, researchers have to assume a correlation between the two. In fact, studies often use erosion as a proxy for SOC movement, because both SOC and 137Cs stick to fine soil fractions (Ritchie et al., 2006). This association has been validated by several experimental studies, among them Ritchie et al. (2006), who measured SOC and soil movement in three sites in Maryland and Iowa and found a correlation between the two.

Rates of detachment and transport

Among the topographic features that influence erosion, slope gradient and length are especially important. It is well established that increased slope gradient and length lead to faster overland water flows, which detach and transport more soil for longer distances. This relationship is seen in several popular models of soil loss, among them the Revised Universal Soil Loss Equation (RUSLE). Soil scientists also agree on the general effect of concavity. On a convex slope, erosion is more significant than on a flat slope, and on a concave slope, erosion is less significant than on a flat slope (Torri and Borselli, 2000).

Soil scientists have also noted relationships between erosion and combinations of topographic features, such as slope gradients in both the down-slope and cross-slope directions. In addition to the traditionally defined segments of a hill (among them, shoulder, backslope and footslope), which are seen only in the hill's profile, slopes may be distinguished by their convergence or divergence, terms that refer to the planar shapes that cause water to either accumulate or disperse. Specifically, soil scientists have defined seven slope segments: convergent shoulders, divergent shoulders, convergent backslopes, divergent backslopes, convergent footslopes, divergent footslopes, and level regions. If water moves fastest over the backslope, it will also have the most volume at the convergent backslope, leading to a high rate of erosion (Lal, 2006).

There is evidence that these patterns apply not only to soil in general, but also to SOC in particular. Ritchie et al. (2006), for instance, found decreasing SOC as slope gradients increased, presumably the result of increasing rates of erosion on steeper slopes. He also found higher levels of SOC on concave slopes than on convex slopes, consistent with the assumption that erosion is higher on convex slopes than on concave slopes.

Topography and biota

Studies of topography often report an indirect effect on SOC via other environmental factors, such as climate. Wiaux et al. (2014), for instance, reported that topography shapes the distribution of soil moisture, with implications for the rate of soil respiration. Specifically, they found that moisture content at the footslope of a hill was 5 percent higher than at the summit and 8 percent higher than at the backslope. This is likely because water runs off the backslope and accumulates at the footslope. As a result, soil respiration was found to be highest at the footslope: 30 percent higher than at the summit. This makes sense, considering that soil microbes benefit from moisture, which carries oxygen and SOC substrate.

Slope aspect has also been found to influence soil climate. Griffiths et al. (2009) reported higher moisture and precipitation, and lower air temperature and soil temperature on a northern exposure than on a southern exposure. In addition, they found significant climatic variation as a result of elevation gain. Specifically, moisture increased and temperature decreased with higher elevation. The implications for microbial communities are complex. While microbes thrive in moist environments, they also prefer warm temperatures (Wiaux et al., 2014). Further, moist climates may be conducive to both microbial communities, which transfer SOC to the atmosphere, and plants, which deposit atmospheric carbon into the soil through their roots. This complexity is apparent in Lenka et al.'s (2013) study of slope aspect and soil respiration, in which they found both higher moisture content and higher SOC stock on a north-facing slope than on an east-facing slope. Whatever the climatic cause, the north-facing aspect was found to be more conducive to SOC accumulation. This suggests that SOC lost by erosion on the north-facing slope will be more easily replaced than on the east-facing slope.

In addition, where slope gradient leads to high rates of erosion, plant communities may suffer, leading to a positive feedback loop. Guzman and Al-Kaisi (2011) reported reduced root biomass on a midslope position, compared to the toe-slope position. Degraded soils at the midslope position, affected by high rates of erosion, meant poor conditions for plant growth. Low plant growth, in turn, predisposed the soil to further erosion.

Transport

Topographic features such as slope gradient and slope length determine the length of time between a soil's detachment and deposition. This has implications for both the amount of mineralization and the amount of stabilization. Wiaux et al. (2014) found that, at the steep backslope position of a slope, where soil was eroded quickly, SOC rarely adsorbed to molecular surfaces, where they would be protected against mineralization. At the backslope, only 30 percent of the total SOC stock was associated with soil minerals, compared with 60 percent at the convex shoulder and 50 percent at the summit (Wiaux et al. 2014). This may be explained by the longer residence time of SOC at the latter positions. Where soil moves quickly across the landscape, SOC doesn't have time to stabilize through adsorption (Wiaux et al. 2014). On the other hand, fast transport may lead to a net carbon sink, because soil is exposed to the atmosphere for less time before burial (Berhe and Kleber 2013).

Deep burial

Deep burial has been identified as an important feature of landscapes in which erosion is a net carbon sink. Therefore, topography is of particular importance because it determines where soils are deposited after erosion. Martz and de Jong (1991) reported an imbalance between sites with net erosion (66 percent) and sites with net deposition (34 percent), which was likely the result of once-exposed soils being buried under layers of other soils. At other study sites, they found evidence of a higher burial rate. Martz and de Jong (1987) found that deposition occurred in 11 to 17 percent of their experimental site. In another study, they found that 90 percent of deposition in a basin happened on less than 3 percent of its area (Martz and deJong, 1985). This pattern of soil burial has implications for SOC. Wiaux et al. (2014) found that soils at the bottom of a slope, where continual erosion caused layering of deposited soils, stored up to two times more SOC than the other slope positions. This makes sense, given that deep soils are characterized by low rates of oxygen diffusion and low nutrient availability, which hinder microbial activity (Chaopricha and Marín-Spiotta, 2014). Indeed, decomposition of SOC is known to decrease with depth (Van Oost et al., 2012, Park et al., 2014). In addition, deeply-buried soils may have high concentrations of SOC simply because they are compacted by overlying soil (Chaopricha and Marín-Spiotta, 2014). High compaction means soils with initially-low concentrations of SOC may be packed together, causing a high concentration of SOC under deep burial. Among the topographic variables that cause deep burial is slope gradient. Steeper slopes have more erosion, and therefore more deposition (Chaopricha and Marín-Spiotta, 2014).

Topography at Carleton

Much of the erosion at Carleton occurs on the edges of campus, where the land slopes toward the Cannon River and Lyman Lakes (Fig. 3). This suggests that much of Carleton's eroded soil is deposited in a river system, where it is quickly mineralized (Wang et al., 2014b)

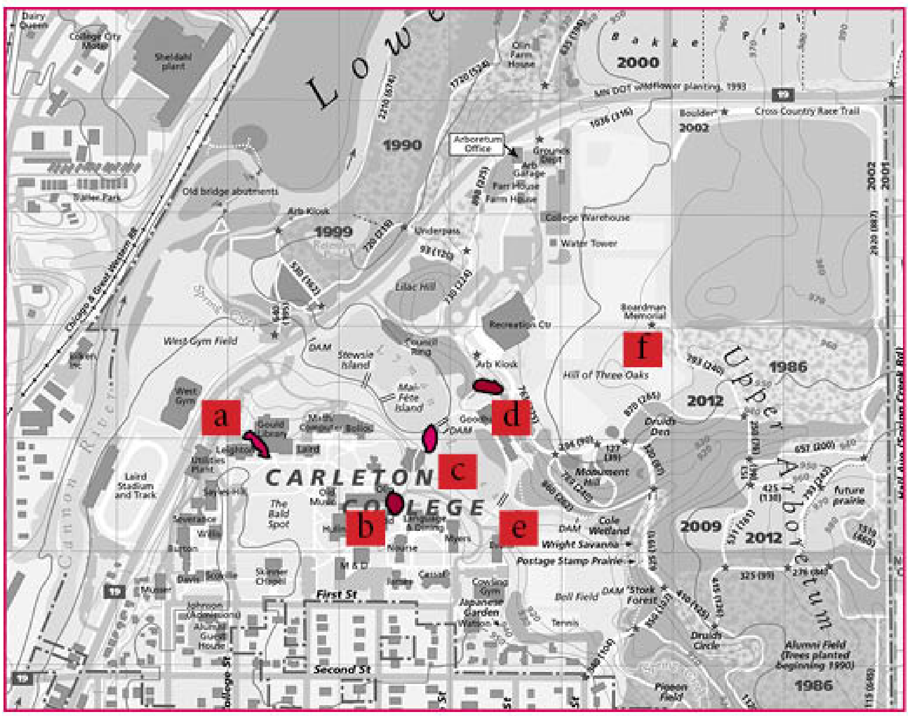

Figure 3. Major sites of erosion at Carleton, identified by Arboretum Director Nancy Braker. Shaded ovals denote eroded hillslopes. (a) is an area between the library and the back door of Leighton, where student foot traffic has destroyed grass cover, leaving barren soil. (b) is another area of intense foot traffic. The Carleton grounds department has attempted to stabilize soil there with a plastic framework to hold soil in the absence of grass (Braker). (c) is at the intersection of two steep, paved paths that descend from Olin and Mudd. (d) is another slope with high foot traffic, going from

Goodhue to the athletic fields. (e) and (f) are places where construction work has revealed barren soil, causing erosion.

Conclusion

Being a multi-step process with great room for variation at each stage, erosion can affect the SOC in many ways. There are no absolutes or formulas to follow when attempting to determine the fate of eroded SOC. However, we can take the various contributing factors that make up the erosional process and closely examine micro-processes that could lead to sinking or releasing of atmospheric carbon. Erosion is a primary force behind environmental degradation. It also severely disrupts agriculture, which has economic implications for the farming industry and leads to food shortage worries in consumers. Because of these implications, erosion's potential for carbon sequestration must be carefully considered before any sort of action plan may be implemented. An increased understanding of the forces at work can help us to better understand how and why erosion could contribute to the ultimate storage of carbon.

Carleton's grounds and arb crews are constantly working to prevent erosion on campus. Where trails were formerly covered by gravel, the crews now cover trails with turf grass to promote stability and prevent erosion (Braker). This also serves to increase SOC in those areas, as plants promote C-sequestration. However, Carleton's Climate Action Plan does not formally describe any current systems in place to terrestrially sequester carbon in the Arboretum or on campus. Though it does state that a recommended future action would be to investigate plant types in terms of their carbon storage potential, it is unclear if these plant types are actually being planted on campus. Erosion is only mentioned in reference to the agricultural land currently being leased to farmers (Carleton Climate Action Plan). We recommend that Carleton's Climate Action Plan Committee investigate erosion with respect to carbon sequestration in order to understand how the widespread erosion occurring on campus could potentially be affecting the atmosphere.

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Geology of Soils

November 2014

The Role of Turf Grass in Carbon Sequestration

Abstract

Global climate change, driven in large part by the increasing concentration of CO_2 in the atmosphere, is a pressing environmental problem. Therefore, it is important to exercise every possible method of removing carbon from the atmosphere and sequestering it. Manipulating soils to store a maximum level of carbon is one approach that should be utilized. Here, a review of the carbon storage in turf grass soils is presented. Factors that influence carbon storage in turf grass are discussed. The turf grass management practices of Carleton College, in Northfield, MN, are compared to best management practices for carbon storage. Finally, an assessment of whether the carbon sequestration potential of turf grass outweighs the carbon costs that go into maintaining turf grass is made.

Introduction

Turf grass covers a significant portion of land in the United States. One estimate says that turf grass accounts for approximately 163,800 km^2 of the coterminous United States, which represents more land than any single irrigated crop (Milesi et al., 2005). This huge area could have the potential to sequester carbon and mitigate the emission of CO_2, a greenhouse gas that contributes to global warming. In order to determine how useful turf grass is in sequestering carbon, though, a detailed investigation is needed. Turf grass's ability to sequester carbon must be compared with that of native groundcovers. It must also be determined how factors including the passage of time and the pH of the soil affect the amount of carbon sequestered by turf grass. Additionally, management practices that enhance carbon sequestration by turf grass should be studied. Finally, an evaluation of whether the carbon sequestered by turf grass exceeds the emissions of CO_2 and other greenhouse gases from the upkeep of the turf grass is necessary in order to determine turf grass's true capacity to decrease greenhouse gas emissions.

Comparison with Native Groundcovers

The efficacy of turf grass in sequestering carbon must be grounded in a comparison between turf grass's ability to sequester carbon and the native groundcover's ability to do so. If turf grass is less effective at sequestering carbon than the native groundcover, then there is little reason to replace the native groundcover with turf grass for this purpose. Turf grass organic carbon and native soil organic carbon were compared in two diverse locations: Denver and Baltimore (Pouyat et al., 2009). In both locations, turf grass soil organic carbon levels were around two times higher than soil organic carbon levels in soils planted with native groundcover for the respective areas (Pouyat et al., 2009). Furthermore, the turf grasses in Denver and Baltimore sequestered similar levels of soil organic carbon, suggesting that turf grass carbon storage may be consistent across widespread regions (Pouyat et al., 2009). These results indicate that implementation of turf grass is a promising method of sequestering carbon and should be further investigated. Whether these results would hold true in southern Minnesota ecosystems is not certain, though.

Other studies indicate, however, that native plants should not be ruled out when planting turf grass with the goal of maximum carbon sequestration (Simmons et al., 2011). Due to native species of turf grass' adaptations to the stresses of their native climate, they may perform better than non-native species of turf grass (Simmons et al., 2011). In fact, native turf grasses displayed 30% greater leaf density than non-native turf grass (Simmons et al., 2011). This higher leaf density may indicate a higher biomass in native turf grasses than in non-natives, which could then facilitate higher carbon sequestration. Although native turf grass growth rates are found to be lower than those of non-natives, a higher plant growth rate does not necessarily yield a higher level of carbon sequestration; the relationship between growth rate and carbon sequestration depends on ecosystem-specific environmental conditions (Simmons et al., 2011; De Deyn et al., 2008).

Effects of Time on Soil Carbon Storage

A relevant factor in turf grass's impact on carbon sequestration is the capacity of turf grass to sequester carbon over time. Decreasing soil carbon sequestration rates after 40 years is reported in turf grass soils on New Zealand golf courses (Huh et al., 2008). A model designed to investigate this subject finds that soil organic carbon in turf grass increased at a rate of 1.2 and 0.9 Mg ha^{-1} yr^{-1} in Fort Collins and Denver, respectively, for 30 years (Bandaranakaye et al., 2003). After 30 to 40 years, the rate of increase of soil organic carbon leveled off significantly, which is in accordance with the study by Huh et al. (Fig. 1) (Bandaranayake et al., 2003). These model results were supported with field evidence (Bandaranayake et al., 2003).

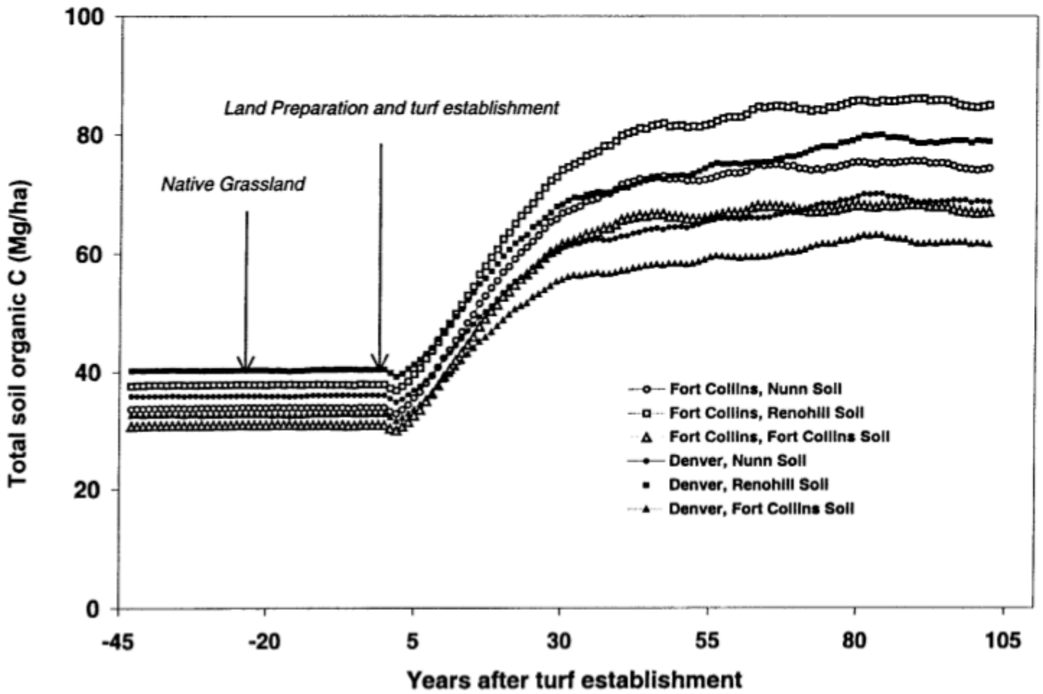

Fig. 1. Effect of time after turf grass establishment on the carbon content of the soil, based on the CENTURY model for three soils planted with fairway turf grass in Fort Collins and Denver, CO. Figure from Bandaranayake et al., 2003.

The above results are roughly consistent with another study that used historical data from golf courses to investigate the impact of time on carbon sequestration by turf grass (Fig. 2) (Qian and Follett, 2002). This study found that the greatest increase in soil organic carbon occurred through 25 to 30 years after turf grass establishment, and that the rate of sequestration during this time period was approximately 0.9 to 1.0 t ha^{-1} yr^{-1} (Qian and Follett, 2002).

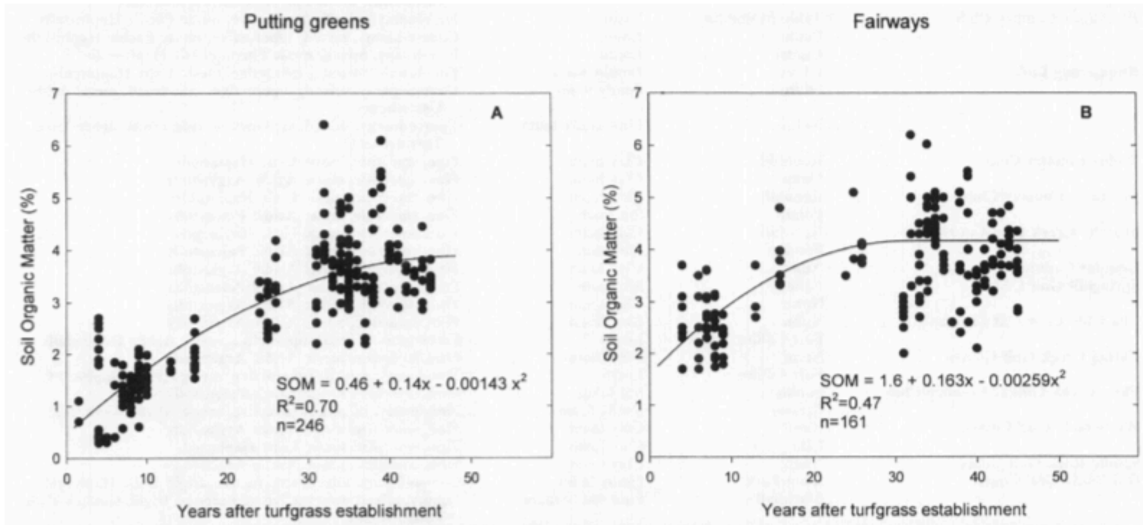

Fig 2. Effect of time on soil organic matter on putting greens (left) and fairways (right) of golf courses in Colorado. Soil was tested to a depth of 11.4 cm. Figure from Qian and Follett, 2002.

Unit conversion allows for a better comparison of these values: 0.9 to 1.0 t ha^{-1} yr^{-1} is equal to .82 to .91 Mg ha^{-1} yr^{-1}. This data is therefore very comparable to the rates of 1.2 and 0.9 Mg ha^{-1} yr^{-1} found by Bandaranayake et al. Comparing total carbon content in a 35 year old urban lawn soil to that in a newly created urban topsoil further reinforces the decreasing ability of a turf grass soil to sequester carbon over time; the 35-year-old lawn had less than 2 kg of total carbon per m^2, while the newly created topsoil contained ~5 kg of total carbon per m^2 (Beesley, 2012).

The previous use of the soil (before turf grass establishment) can also have an impact on the carbon sequestration potential of the soil once turf grass had been established (Qian and Follett, 2002). Areas that previously supported agriculture had lower soil organic carbon contents by 24% than areas that were previously native grasslands (Fig. 3) (Qian and Follett, 2002). It is thought that this difference is due to the oxidative losses of soil organic carbon that can occur in highly managed agricultural soils (Qian and Follett, 2002).

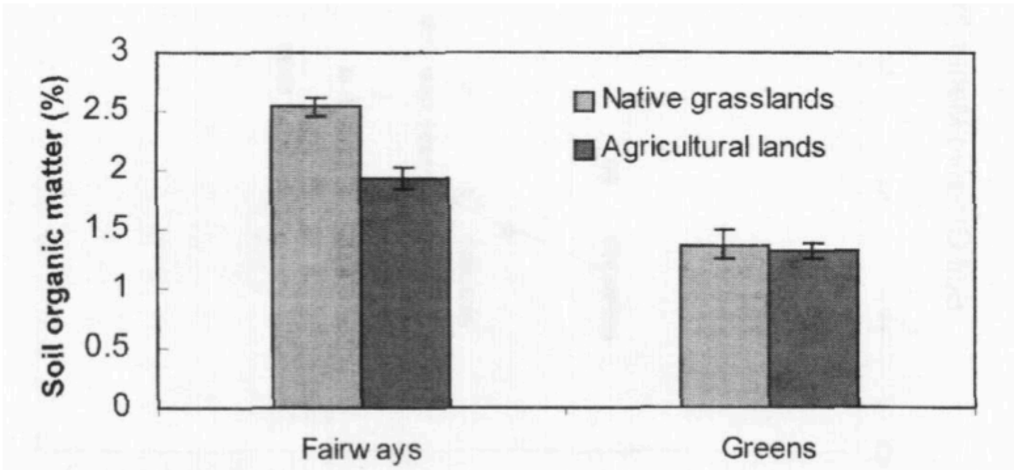

Fig. 3. Effect of past land use on soil organic matter in the surface (11.4 cm) soil of fairways and putting greens. All turf grass was younger than 10 years. Vertical lines represent standard errors. Figure from Qian and Follett, 2002.

Effect of pH on Soil Carbon Storage

It is thought by some that a soil's pH can impact its potential to retain soil organic matter and by extension store carbon, but the relationship between pH and carbon storage in soil is not well understood. Soil organic matter has been shown to decrease as pH increases above 7.3 and soils become more alkaline (Qian and Follett, 2002). For soils with pH of less than 7.3, soil organic matter does not change with pH (Qian and Follett, 2002). However, these results are contradicted by another study that found that soil carbon was approximately 12% greater in a site with alkaline soils than in a site with acidic soils, and that the accumulation rate of soil C was approximately 3 times higher in the alkaline site than in the acidic one (Yao et al., 2010). This difference could be attributable to microbial activity, which can be regulated by pH (Yao et al., 2010). The inconsistent results of these two studies demonstrate that the effect of pH on soil carbon is not certain.

Effects of Management on Carbon Storage

The management of turf grass plays a significant role in the amount of carbon that the turf grass can sequester. Management practices that affect carbon sequestration include clipping removal or retention and fertilization.

Clipping Removal versus Retention

An aspect of management that can affect soil carbon sequestration by turf grass is the treatment of the clippings after the turf grass has been mowed. Model simulations to investigate this relationship find that returning the clippings to the grass after mowing instead of removing the clippings can increase carbon sequestration by 11% to 25% under regimes of low nitrogen fertilization, and by 11% to 59% under regimes of high nitrogen fertilization (Qian et al., 2003). These results are probably due to the fact that returning clippings after mowing adds a source of nitrogen to the soil, which promotes growth of the plant's biomass (Qian et al., 2003, Lopez-Bellido et al., 2010). Another model further supports the finding that retention of grass clippings increases soil carbon sequestration (Milesi et al., 2005). According to this model, the largest carbon fluxes (and therefore largest quantities of sequestered carbon) were recorded in turf grasses with the highest applications of nitrogenous fertilizer and with clippings left on the grass after mowing, but the lowest carbon fluxes were recorded in turf grasses with the same high level of nitrogenous fertilization but with clippings removed after mowing (Milesi et al., 2005). Therefore, it seems that clipping management has a greater effect than fertilization on carbon sequestration by turf grass. However, fertilization is also an important management factor to consider for the sequestration of carbon.

Fertilization

Fertilization can promote carbon sequestration by turf grass by improving the plant's growth and health (Lopez-Bellido et al, 2010, Milesi et al., 2005). One type of fertilizer that can promote carbon sequestration by turf grass is plant growth regulator (henceforth referred to as PGR) (Lopez-Bellido et al., 2010). PGR is applied to managed turf grasses to increase grass density, make grass more able to withstand environmental hardships, and reduce the amount of mowing that is necessary to maintain the grass (Lopez-Bellido et al., 2010). PGR affects turfgrass by increasing its root mass, which would increase carbon sequestration by increasing overall plant biomass (Lopez-Bellido et al., 2010). Experiments support this reasoning: soil organic carbon in grasses with PGR applied was higher at all depths between 0 and 15 cm than in grasses without PGR (Lopez-Bellido et al., 2010). Below 15 cm, soil organic carbon levels are approximately equal for grasses with and without application of PGR, probably because plant roots did not reach this far into the soil (Lopez-Bellido et al., 2010).

Another fertilization practice that can affect turf grass carbon sequestration is the application of nitrogenous fertilizer (Lopez-Bellido et al., 2010, Milesi et al., 2005). Because nitrogenous fertilizer increases the biomass of plants, it is thought to increase the amount of carbon sequestered by the plant. According to Milesi et al., carbon fluxes (and by extension carbon stored) were highest for turf grasses that had received the highest applications of nitrogenous fertilizer (and had clippings left on the soil after mowing) (Milesi et al., 2005). Another study found that application of nitrogenous fertilizer increased the carbon stored in soil down to 2.5 cm, and that below that level there was no difference between turf grasses with and without application of nitrogenous fertilizer (Lopez-Bellido et al., 2010). Therefore, it is clear that nitrogenous fertilizer has a positive effect on soil carbon sequestration, even if only in the top few inches of the soil.

The effects of management on soil carbon may not always behave as described above, however. In a study in Auburn, Alabama, there was not a significant relationship between soil carbon and fertilization, or between soil carbon and clipping treatment (removal versus retention) (Huyler et al., 2014). The lack of expected relationships between soil carbon and clipping treatment, and between soil carbon and fertilization could be due to the very humid climate of the study site in Alabama, which may promote residue decomposition and the release of soil carbon (Huyler et al., 2014). Similarly, another study found that if too much application of nitrogenous fertilizer was applied to turf grass, decomposition and loss of soil carbon was elevated, and carbon sequestration was therefore decreased (Wang et al. 2014).

Carleton's Management Practices

Carleton's management of turf grass includes the retention of mowed clippings, which will enhance carbon sequestration by turf grass on Carleton's campus (Stadler, 2014). Fertilization of turf grass on Carleton's campus is handled with care; a minimal amount of synthetic fertilizer is used to lessen the run-off of nitrogen into the water systems and the release of greenhouse gas N_2O into the atmosphere (Stadler, 2014). However, some levels synthetic fertilizer are used with the goal of promoting healthy turf grass, and by extension promoting the sequestration of carbon by turf grass (Stadler, 2014). Fertilizers are strategically applied to the areas that are most in need of them

(Stadler, 2014). Carleton prioritizes the health of its turf grass above its appearance or color, which should serve to maximize carbon sequestration, since health and plant biomass are often linked (Stadler, 2014). Carleton's turf grass management aligns with the best management practices for promoting carbon sequestration described above.

Cost-Benefit Analysis

The management practices that optimize carbon sequestration in turf grass do not have exclusively positive impacts on the environment as a whole (Milesi et al., 2005; Townsend-Small et al., 2010; Bartlett et al., 2010). The nitrogenous fertilization practices that have a positive impact on soil organic carbon can be a source of greenhouse gas emissions even while aiding the turf grass in sequestering carbon (Bartlett et al., 2010, Townsend-Small et al., 2010). Specifically, nitrogenous fertilizers release N_2O into the atmosphere, which is a greenhouse gas that is approximately 300 times as potent as CO_2 (Townsend-Small et al., 2010). Furthermore, significant watering is necessary for upkeep of healthy turf grass that is capable of sequestering carbon, but this watering puts a stress on the limited water resources in the U.S., especially in arid regions (Milesi et al., 2005). Therefore, watering all the U.S.'s turf grasses with the goal of maximum carbon sequestration would be an irresponsible use of water resources (Milesi et al., 2005). And operating mowing machinery releases CO_2 at a rate of approximately 1469 g m^{-2} yr^{-1}, based on turf management in parks (Townsend-Small et al., 2010). The carbon emissions associated with these and other management practices are quantified in Figure 4.

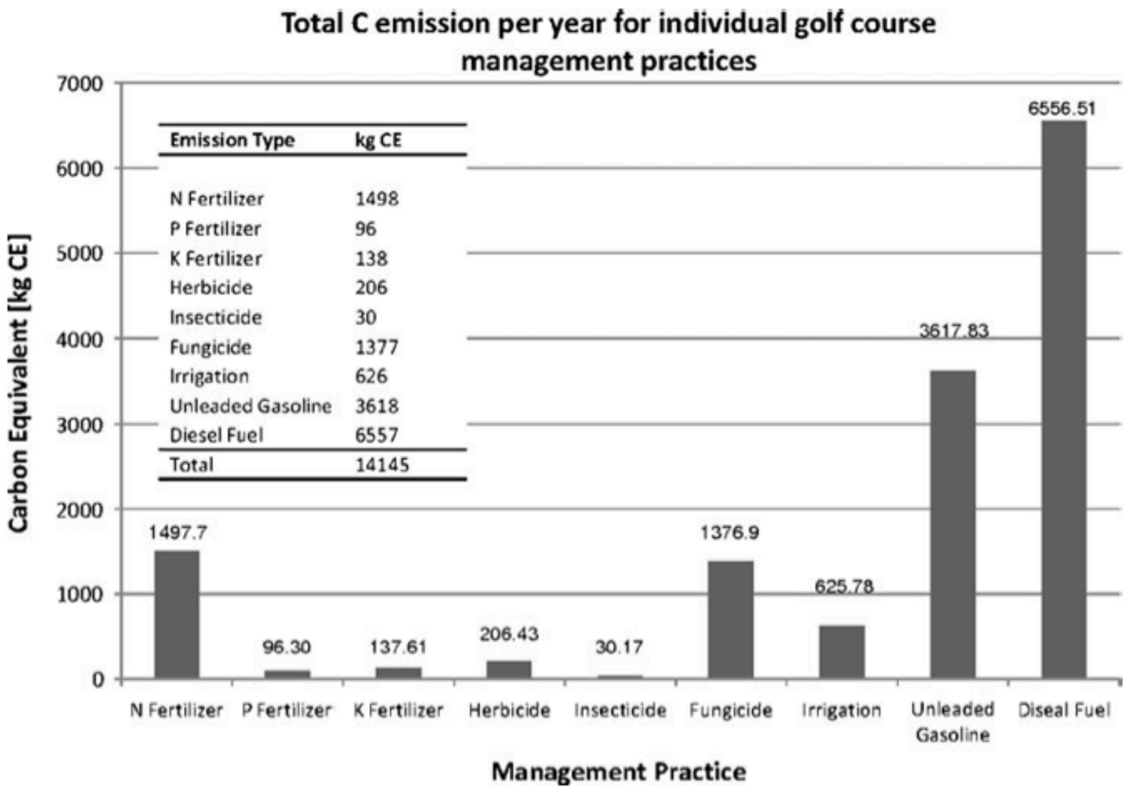

Fig 4. Estimations for the carbon emissions (in kg of Carbon equivalent units) per year for golf course management practices. Data is from a 46.77 ha golf course in central Ohio. Figure from Selhorst and Lal, 2011.

One study attempted to synthesize the costs and benefits of managing turf grass by calculating turf grass' net impact on CO_2 levels in two golf courses (Bartlett et al., 2011). According to this study, turf grass on the golf courses were found to add a marginal amount of CO_2 to the atmosphere: one course emitted a net 0.4 ± 0.1 Mg CO_2e ha^{-1} yr^{-1}, and the other emitted a net 0.7 ± 0.2 Mg CO_2e ha^{-1} yr^{-1} (Bartlett et al., 2011). These emissions were due to the management practices necessary for the upkeep of the turf grass (Bartlett et al., 2011). This calculation and the resulting net impact on CO_2 by managed turf grass could be changed depending on the management practices used on that turf grass, however.

Examination of golf course turf grasses and maintenance revealed that when both the carbon sequestered by the soil and the carbon emitted as a result of turf grass maintenance were considered, turf grass golf courses transitioned from acting as sinks of carbon (sequestering carbon) to acting as sources of carbon (emitting carbon) within 30 years (Selhorst and Lal, 2011). An equivalent study in Hong Kong determined that this transition from carbon sink to carbon source occurred even sooner: between 5 and 24 years (Kong et al., 2014).

CO_2 emissions from turf grass management could be decreased with lessened cutting, because this would decrease emissions from mowing machinery. Therefore, the slower growth rate of some native turf grass species compared to non-native turf grasses could help to lower the CO_2 emissions of turf grasses, because they would require less frequent mowing (Simmons et al., 2011).

Conclusion

Although turf grass has the potential to sequester carbon and remove CO_2 from the atmosphere, carbon sequestration by turf grass is a complex and even controversial topic. Turf grass can be more effective than native soils at sequestering carbon, and can maintain its ability to sequester carbon for 25 to 40 years (Pouyat et al. 2009, Huh et al. 2008, Qian et al. 2003, Bandaranayake et al. 2003). To maximize carbon sequestration by turf grass, management practices should involve retention of clippings and fertilization (Qian et al. 2003, Milesi et al. 2005, Lopez-Bellido et al. 2010). Carleton's turf grass management is aligned with these practices, which bodes well for carbon sequestration by turf grass on campus (Stadler 2014). However, the high levels of fertilization and watering that are necessary to maximize carbon sequestration by turf grass have negative environmental impacts that might actually offset any positive effects of the turf grass itself on stored carbon (Milesi et al. 2005, Townsend-Small et al. 2010, Bartlett et al. 2011, Selhorst and Lal, 2011, Kong et al. 2014).

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PLANT TRAITS AND CARBON SEQUESTRATION

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Mary Savina
Geology of Soils
19 November 2014

Abstract

Carbon sequestration is one of the most prominent mechanisms for slowing the rise of greenhouse gases in the atmosphere and perhaps preventing serious global climate change. Plant types can have a large impact on how much carbon is sequestered in the soil. There are two main ways in which plants affect soil carbon sequestration: by increasing soil carbon input and by decreasing soil carbon loss. Soil carbon input is increased mostly by increasing the plant biomass that enters the soil. This can be achieved by plants with faster growth rates and relatively large root mass. Plant growth rate can be further excelled by symbionts that provide limiting nutrients like nitrogen. Soil carbon loss can be slowed by decreasing plant respiration and plant decomposition rates, and by combating soil erosion and weathering (which certain plant characteristics, like root strength, can do). Based on a survey of scientific literature, it was determined that one of the best methods for positively influencing soil carbon sequestration in southeastern Minnesota is planting a diverse mix of Nitrogen fixing legumes and C4 grasses with large amounts of below ground biomass.

Introduction

With rising levels of CO_2 in the atmosphere, scientists are looking for new ways to influence the effects of climate change. The soils of the planet contain one of the biggest carbon reserves in the world. As such, it is pertinent to look for ways to maximize carbon sequestration in the soil in order to return more carbon back to the earth, where it is less detrimental to the atmosphere. This is directly influenced by the plant life that exists and contributes to the formation of soil. For example, managing tree species in forests has been suggested as a mitigation strategy (Vesterdal et al., 2008). Root and plant litter play an essential role in the carbon cycle, and soil carbon mostly originates from decaying aboveground and belowground plant tissue (De Deyn et al., 2008). Different plants have various traits that control carbon sequestration, including growth rates, decomposition rates, and influence on respiration. Depending on what traits a plant type has, the carbon moving between the soil and the atmosphere cycles either faster or slower, and more or less carbon remains in the soil. Soil carbon is lost through decomposition, erosion and fire and is gained through plant respiration and growth. To maximize soil carbon sequestration and minimize soil carbon loss, it becomes essential to investigate which plant traits influence sequestration in the most beneficial way. Once we have done that, we will seek to answer this question: what is the ideal combination of plant types to maximize carbon sequestration on the Carleton College campus? To answer this, we investigate how plants contribute to the carbon cycle and identify specific plant traits that contribute to increasing soil carbon input and decreasing soil carbon loss.

II. Plants in the Carbon Cycle

In the continued process of carbon moving from the atmosphere to the earth and back again, plants play a key role in the conversion from carbon as a gas (CO_2) to soil organic carbon (SOC). Plant life is the primary source of organic material deposition into the soil (Orwin et al., 2010). Through root respiration and plant decomposition, carbon enters the soil and becomes a part of the soil formation. See Figure 1 for a visual representation of the carbon cycle (Figure from Amundson, 2012).

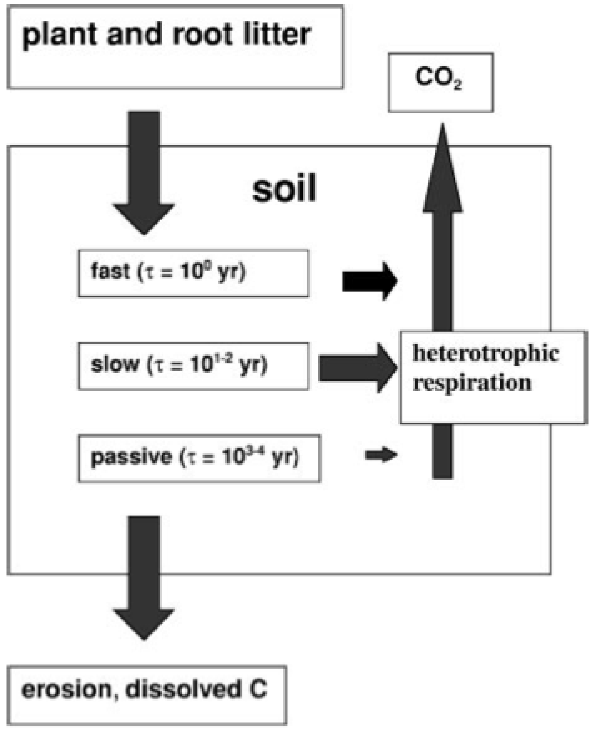

Figure 1. *A simple schematic diagram of the soil C cycle.*

The carbon stored in the body of a plant enters the soil through the process of death and decomposition. As evident in Figure 1, plant life has an influence on both the speed and amount of carbon sequestration. Plant decomposition additionally influences the length of time carbon remains in the soil once sequestered. After entering the soil, the SOC remains for a duration of time, depending on the type of plants that are and were present in the environment, among other factors. Therefore, we decided to divide our investigation between plant traits that increase soil carbon sequestration and plant traits that decrease soil carbon loss.

III. Plant Traits That Increase Soil Carbon Input

Plant Growth Rate

SOC levels can partially be attributed to plant growth rate. Characteristically, fast-growing plants have high photosynthetic ability that allows them to grow quickly. The large amount of active roots and leaves input high amounts of carbon to the soil (Erfanzadeh et al., 2014). However, the speed of fast-growing plants is balanced by their short lifespan and the relatively low carbon concentration in the plant tissue (Aerts & Chapin, 2000). One study indicates that fast-growing plants are less effective at sequestering carbon due to the low density of the plant structure and relatively quick decomposition rates (De Deyn et al., 2008).

By contrast, slow-growing plants contain more carbon within the plant structure, and decompose more slowly, leading to longer lasting sequestration of carbon within the soil. However, slow-growing plants are also often nutrient-poor and do not contribute much carbon to the soil through root respiration (De Deyn et al., 2008). Though slow-growing plants do not input such high amounts of carbon into the soil, the higher concentrations of carbon of their tissue decays less rapidly, suggesting that slower-growing plants increase carbon sequestration.

The literature is not entirely consistent on the cumulative influence of plant growth rate on SOC. In another study of plant traits within grassland species, researchers found that species with higher growth rates actually were associated with a slow decomposition rate, which would be beneficial for SOC sequestration (Orwin et al., 2010). This could be explained by the acknowledgement of an indeterminate number of factors that are influenced by plant growth rate, but influence SOC in different ways. Plants with fast growth rates tend to produce more nutrient rich plant litter, which encourages more fast-growing plants, and therefore encourages more C sequestration. Therefore, despite the characteristics of fast-growing plants that do not contribute to SOC sequestration, there is the possibility that fast-growing plants have additional characteristics that may indirectly positively influence SOC (Orwin et al., 2010). This contrast between the relevant traits of fast- and slow-growing plants does not make it clear which type of plant inputs the most SOC. Another example of the complex influence of plant life is regarding the speed of plant growth. This is often dependent upon the type of biome. Fast-growing plants flourish in productive biomes with nutrient rich soil, where their speed of growth is not limited. In less productive biomes with short growing seasons, slow-growing plants flourish, leading to the most carbon input (De Deyn et al., 2008).

The most obvious conclusion to draw from the literature regarding speed of plant growth in relation to SOC sequestration is that there is still a lot of research to be done. The relationship between plant growth rate and SOC is clearly influential, but it is also complex and not fully investigated. Plant growth rates are related to other plant traits and environmental factors, which influence the soil carbon in inconsistent ways. However, regardless of plant growth rate, it was well established by a study conducted by Fornara and Tilman (2008) that the amount of belowground plant biomass relates positively to soil carbon accumulation (Figure 2). Speed of plant growth is complex and related to many other factors, including soil fauna (Vetter et al., 2002). Therefore, it is unclear which would result in the highest belowground biomass. Therefore, it becomes important to examine the other plant traits that influence SOC sequestration.

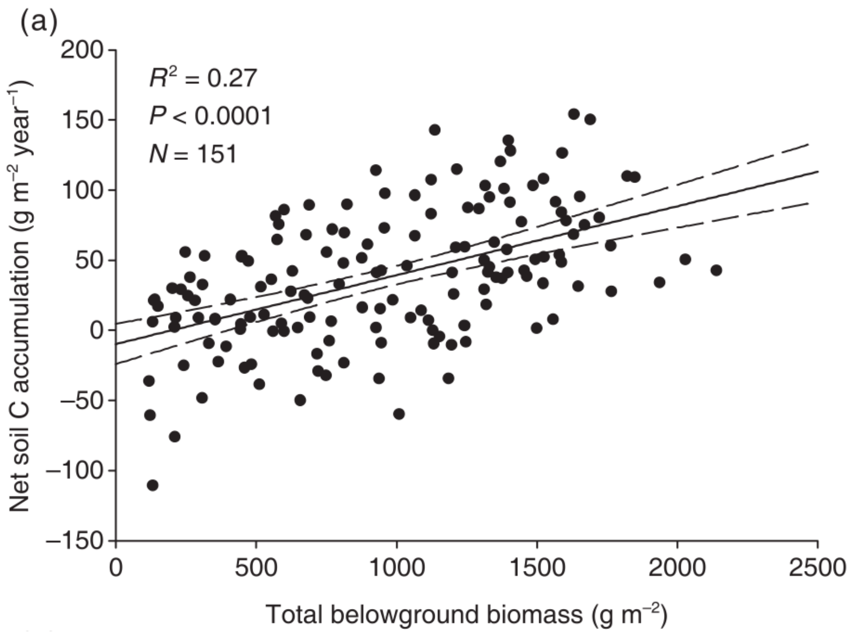

Figure 2. *Total belowground biomass vs. Net soil carbon accumulation. (Fornara & Tilman, 2008)*

Symbionts

N-fixing plants and mycorrhizal fungi increase primary plant productivity, and therefore increase SOC (De Deyn et al., 2008). Because nitrogen is often the limiting factor to plant growth, it is recommended that nitrogen be added to increase above ground plant productivity and CO_2 uptake (Erfanzadeh et al., 2014; Batjes, 1998). An alternative method to increasing nitrogen availability is to plant nitrogen fixing plants. Nitrogen fixing plants, like legumes, have a symbiotic relationship with N-fixing bacteria that forms nodules on plant roots. Especially in N-limited biomes, planting species that increase the nitrogen fixing capabilities of the soil increases plant growth potential. Indirectly, this also increases the potential carbon uptake of the soil, especially in young soils (Amundson, 2001). According to a study by D.A. Fornara & D. Tilman, legumes have a positive influence on soil nitrogen. However, it was also determined that the legumes were by far more effective when growing in conjunction with C4 grassland species. Through the symbiosis of these different species, the nitrogen fixing capabilities rose significantly (Fornara & Tilman, 2008). It notable that besides the N-fixing capabilities of this relationship, the legumes and C4 grasses have additional plant traits that give them a competitive advantage, including differing decomposition rates and litter quality (Fornara & Tilman, 2008). See Figure 3 for an example of how an increased numbers of species, with C4 and nitrogen fixers, increased soil carbon accumulation.

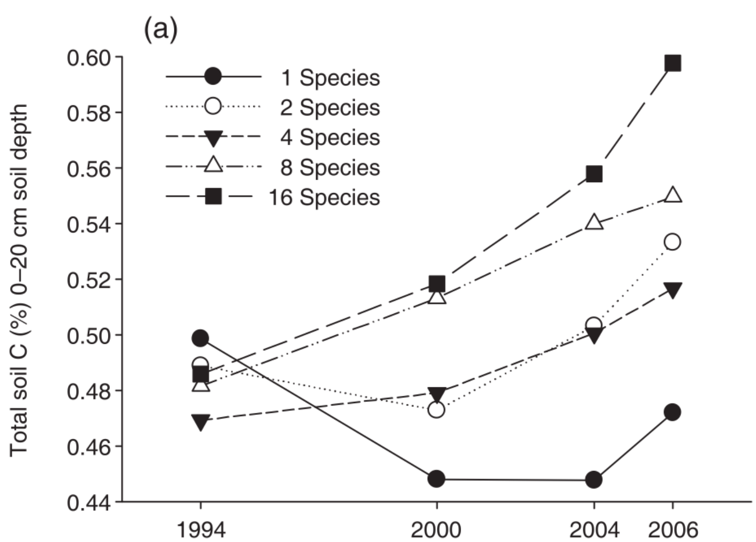

Figure 3 *Total soil carbon over time for plots with 1, 2, 4, 8, and 16 different species. (Fornara & Tilman, 2008)*

Mycorrhizal hyphae are another symbiotic species that increases nutrient availability in the soil. They are a fungi that colonize nearly 80% of plant roots in almost every habitat of the world (Treseder & Allen, 2000). Elevated levels of nitrogen and phosphorous directly improve primary productivity, which in turn increases SOC (De Deyn et al., 2008). A study by Wilson et al. in 2009 concluded that extramatrical mycorrhizal hyphae increase the proportion of macroaggregates, thus stabilizing soil and reducing SOC loss. The formation of such aggregates relocates carbon away from high respiratory areas around plant roots and into the soil matrix. To add to this conclusion, they were the first to observe a reduction in soil aggregation associated with the application of fungicide that exterminated extramatrical mycorrhizal hyphae. The lack of aggregation that provided physical protection to carbon in the soil and improved nutrient turnover rates thus increased soil carbon loss. This presumably decreased the soil's effectiveness as a carbon sink.

III. Plant Traits That Decrease Soil Carbon Loss

Soil respiration is responsible for the largest amount of carbon loss from soil (De Deyn et al., 2008). The respiration from heterotrophs' and autotrophs' microbes converts soil carbon back to CO_2, which releases carbon from the soil into the atmosphere (Amundson, 2001). However, detailed knowledge regarding the specific influence of heterotrophs on soil carbon loss is not yet available, due to the difficulties in distinguishing the influence of heterotrophs, symbionts, and the plants themselves on SOC loss. Plants impact respiration processes directly through root respiration. They impact respiration processes indirectly by controlling heterotrophic respiration, decomposition, and assimilation (De Deyn et al., 2008).

Plant Respiration

Fast-growing plants have high concentrations of nutrients in their plant tissues, including nitrogen. High nitrogen levels are maintained by elevated metabolic activity, and are positively correlated with respiration rates. Thus, carbon loss through high levels of respiration is most common in fast-growing plants (Orwin et al., 2008). Though this statement may be carried over to plants with symbionts, the net effect on soil carbon may be altered by below-ground activity regarding mycorrhizal fungi and nitrogen fixing roots. Whether this effect is large enough to override the carbon loss due to elevated respiration is specific to the specific symbiotic relationship (Allen et al., 2003; Kiers & van der Heijden 2006).

Decomposition

As mentioned above, the speed of growth of a plant has an influence on the amount of carbon that is sequestered in the soil. Speed of growth is directly correlated with speed of decomposition, which additionally has an effect on soil carbon. Fast-growing plants distribute little of their energy to structural stability, and therefore decompose quickly. The fast decomposition quickly releases carbon from the soil, often overriding the potential benefits that the extra nutrients provide toward an increase of primary productivity. Further, such nutrient rich plants are naturally weeded out because they are preferable to herbivores and are eaten first. This preference increases the ratio of slow to fast growing plants, though the noticeable change presumable varies greatly between ecosystems (De Deyn et al., 2008).

Slow-growing plants are often long-lived and store carbon in organs devoted to structural stability. This often results in woody structures, which are nutrient poor but carbon rich. The resulting litter of slow-growing species is tough, woody, recalcitrant, and difficult to decompose (Macias & Marta, 2010). Slow soil organic matter consists of these recalcitrant components, including chitin and glomalin, and might last from years to decades in the soil (Treseder & Allen, 2000). Due to the long time it spends residing in the soil, the slow decomposition of recalcitrant litter enables greater carbon storage (De Deyn et al., 2008). For example, a 2014 study by Huyler et al. found that trees in a turf grass yard setting contribute to an increased soil carbon at a depth of thirty to fifty centimeters. Slow-growing cryptograms, like ferns, further slow decomposition because they contain high amounts of secondary carbon compounds (Huyler et al., 2014). In all types of plant species, root litter is generally more recalcitrant than litter from the rest of the plant body (shoots) (De Deyn et al., 2008). Thus, it is suggested that plants with a higher ratio of roots to shoots will form more recalcitrant litter.

Erosion Prevention

In addition to the physical presence and decomposition of plant life on a soil, living plants have another important property that reduces soil carbon loss. Root structures provide stability and prevention against erosion of a soil, especially in the presence of steep slopes. This characteristic has been overlooked in favor of looking at respiration and decomposition, but its influence is perhaps more important than previously assumed (Amundson, 2001). Physical traits, such as root abundance and depth, stabilize soil carbon levels within a soil by reducing the effects of rain and wind (De Deyn et al., 2008). Depending on the root traits, plants are more or less effective at stabilizing the soil. Grass species have large root systems and are more effective at forming a stable, sod-like piece of earth than trees, which extend fewer deep roots. Therefore, plant roots not only influence soil carbon through respiration and decomposition, but also by stabilization (Conant 2001).

Aboveground Characteristics

Aboveground physical traits of plants can also have an effect on decreasing SOC loss. Plants can have a strong effect on the microclimate and the temperature of the soil. Mechanisms for this include vegetation canopies changing the albedo, altering apparent wind speed at the soil level, and affecting the snow cover in certain areas. Plant cover can serve to insulate the soil from the leaching, weathering, and erosive effects of temperature and climate. (De Deyn et al., 2008) Keeping plant cover is important because chemical weathering processes can mineralize SOC, changing the way that it is trapped in the soil. Additionally, soil temperature affects the way that SOM decomposes, which changes the amount of time that carbon remains sequestered in the soil.

V. Conclusion

In this paper we have identified various traits in different plants that contribute to the sequestration of soil carbon in the soil. These include traits that increase soil carbon input, such as plant growth rate and symbiotic relationships, as well as traits that decrease soil carbon loss, which include low plant respiration rates and low decomposition rates. Since there are no plant species that possess all of the ideal characteristics that maximize soil carbon sequestration, it appears that there are no exclusive plant species or families that are universally more beneficial for carbon sequestration. Different traits have different advantages, and this must be taken into consideration. The value placed on different traits varies between biomes. However, based upon the papers we looked at, the most effective carbon sequestration planting strategy does not hinge solely on one type of plant being much better than the others. Instead, it seems that diversity of plant life is the key factor to effective carbon sequestration. For example, legumes and C4 grass work much better planted together to sequester carbon than each separately, as the legumes fix more nitrogen into the soil, allowing the C4 grasses to grow more biomass and trap more carbon (Fornara & Tilman, 2008; Conant et al., 2001). On Carleton's campus, implementation of a planting strategy focusing on carbon sequestration should include diverse beds of prairie legumes and C4 grass. Not only do these plants effectively sequester carbon, but they are native to the prairies of Southeastern Minnesota. Therefore, they would likely grow without the need for excessive caretaking. Additionally, the increased planting of trees and woody shrubs, which produce recalcitrant litter, will sequester carbon for a longer period of time. However, due to the restrictions inherent in planning a college campus, the prairie grasses and trees likely could not entirely replace turfgrass. Other studies will address the carbon sequestration potential of turfgrass and its alternatives. Essentially, it is evident that the influence of plant life on carbon sequestration and maintenance is complicated and not yet fully researched. More studies on the way plants relate to soil carbon storage would greatly improve the effectiveness of a campus carbon sequestration planting strategy.

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Jackson Van Fleet
Perrin Stein

Effects of ecosystem, molecular properties on carbon sequestration

Abstract

Reducing atmospheric CO_2 is essential to preserving the Earth. Large pools that turn over slowly remain carbon sinks for long enough to offset the anthropogenic increase of atmospheric CO_2. The largest sink with the longest turnover time is soil. Therefore, examining current soil organic carbon (SOC) stocks and rates of SOC sequestration over time are the key to creating land-use management practices for a sustainable future. To better understand SOC stocks and rates of sequestration, we asked: What ecosystem and molecular factors influence rates of SOC sequestration, how do these rates change as a result of a change in land-use, and how can we use this knowledge to increase SOC sequestration at Carleton College? To answer these questions, we will evaluate the ecosystem properties and the molecular properties that influence rates of SOC sequestration, as well as how these properties affect SOC sequestration at ecosystem equilibrium and after a land-use change. We will conclude with a synthesis of current models that quantify SOC ecosystem and molecular properties in order to understand SOC sequestration rates over time. These models show how knowledge about rates of SOC sequestration can be applied to reduce atmospheric CO_2. Based on the literature we read, it is clear that current knowledge of SOC sequestration is incomplete and inconsistence, making it difficult to create SOC sequestration models that shed light on land-use management practices that will harness the potential of terrestrial SOC sequestration at places like Carleton College.

Introduction

Soil scientists and agronomists are shifting away from the paradigm that views a soil solely as a function of soil parameters (Jenny, 1994) and towards the view that soils are components of ecosystems (Schmidt, et al., 2011). Increasingly, soils will be managed based on the idea that a “healthy” soil is part of an ecosystem (Carol Adair, et al., 2009). Land managers will have to ask themselves how it is possible to emulate ecosystem properties in order to promote a particular use for their soils.

Carleton College is committed to mitigating climate change (Committee, 2011). Because soils store approximately twice as much carbon as the atmosphere (Greiner, et al., 2013, Trumbore, 2000), one way for Carleton to address its carbon footprint is to seek ways of sequestering carbon via land management decisions (Committee, 2011, Specht, 2009). The Cowling Arboretum, with an area of approximately 360 hectares (Braker, 2014) is being actively restored from agricultural use to native prairie and is thought to diminish the College's carbon footprint because prairies have a greater capacity to add carbon to soil (Specht, 2009). Besides the Arboretum, the Carleton College main campus, which covers an area of approximately 56 hectares (Case, 2012), could be managed to better sequester soil organic carbon (SOC).

The SOC storage potential of a soil is better assessed based on factors that influence SOC than based solely on the size of the carbon stock itself (Trumbore, 2000). Therefore, SOC sequestration at Carleton can only be understood if the factors—both ecosystem and molecular—that cause SOC sequestration rates are understood.

This literature review is part of a body of reviews compiled by the Geology of Soils class, fall 2014, which assesses the carbon storage potential of the Carleton main campus. This review attempts to examine current data on changes in SOC sequestration through time as a result of changes in soil molecular and ecosystem properties, as well as from movements to and away from equilibrium. We will first look at the ecosystem and molecular soil properties that affect SOC sequestration in an ecosystem equilibrium, then we will look at the effects of a land-use change on SOC sequestration, and we will end with a look at how current knowledge on SOC sequestration is used to make models that help soil scientists and agronomists determine land management strategies that reduce atmospheric CO_2.

Ecosystem properties affecting SOC sequestration

To understand how SOC sequestration changes over time, it is essential to know what factors influence SOC (Schmidt, et al., 2011). Ecosystem properties are essential to understanding SOC sequestration because soil, soil organic matter (SOM), and SOC change the terrestrial biome and the terrestrial biome changes soil. Based on the literature reviewed for this paper, the ecosystem properties that have the greatest influence on SOC sequestration are roots, soil heterogeneity, soil structure, vegetation, and climate.

Roots

A study using biomarkers showed that carbon in subsoils was most commonly derived from roots, not the plants themselves, as was previously understood (Mendez-Millan, et al., 2010). Another showed that an increase in SOC was associated with standing root biomass (Carol Adair, et al., 2009). Roots may also be responsible for "priming" microbial activity in the subsoil, and thus, the extent to which roots sequester SOC versus promote carbon turnover is still uncertain (Kalbitz, et al., 2000). Because there is no comprehensive understanding of the effects of roots on SOC sequestration rates, it is clear that roots are an important factor in SOC sequestration and therefore need to be researched further.

Soil Heterogeneity

Soil heterogeneity also influences SOC sequestration and decomposition. Carbon compounds are decomposed, which is the opposite of sequestration, only after coming into contact with a specific subset of the soil microbiome. Therefore, soil heterogeneity, and the processes that cause it, influence SOC sequestration (Schmidt, et al., 2011). High microbial activity increases rates of SOC and SOM decomposition, which decreases rates of SOC sequestration (Bala, et al., 2013). Because microbes move in pore spaces that are saturated with water, the more water and pore space a given soil has the less capacity it has for SOC sequestration (Greiner, et al., 2013). In addition, bioturbation moves microbes throughout the soil, facilitating SOC decomposition (Bala, et al., 2013). Therefore it follows that ecosystems with less water, less pore space, and less bioturbation are better at sequestering SOC.

Vegetation

Vegetation is an essential part of every ecosystem, so it can help explain SOC stocks and rates of sequestration. Because SOC comes from SOM, organic horizons (surface-level plant litter), and humus, it is clear that rates of SOC are tied to type of vegetation (Schulp, et al., 2013). However, there is no consensus on what type of vegetation gives a system the highest SOC stock and rate of sequestration. For example, Post and Kwon (2000) found that cultivated crops have more soluble material than perennial grasslands, so they decompose more readily and are therefore bad at SOC sequestration. However, Kalbitz et al. (2000) found that vegetation that decomposes quickly does not necessarily have poor SOC sequestration, meaning that Post and Kwon's (2000) results do not necessarily mean that crops are worse at sequestering SOC than grasslands.

It may be better to look at the carbon-nitrogen ratio by mass of vegetation to understand SOC sequestration rates (Carol Adair, et al., 2009). The higher ratio of carbon to nitrogen results in a higher rate of decomposition. This means that a plant with a higher carbon to nitrogen ratio is worse at sequestering SOC (Bala, et al., 2013). In addition, plant density may help explain SOC sequestration. In a study of seagrass restoration, Grenier et al. (2013) found that increased density of vegetation consistently increased SOC sequestration, suggesting that perhaps quantity of vegetation matters more than the type of vegetation. It is important to note that plants cannot be looked at independent of the ecosystem in which they live because plants affect soil pH and soil heterogeneity, which affects microbial activity, and this, in turn, affects rates of SOC decomposition and sequestration (Zhou, et al., 2009).

Climate

Numerous studies detail the importance of climate in determining rates of SOC sequestration. Higher temperatures catalyze reactions. Therefore, as the Earth warms, the rates of SOC decomposition and of plant respiration increase, which release more SOC into the atmosphere and calls into question the potential of terrestrial SOC sequestration (Hajima, et al., 2014, Trumbore, 2000). Furthermore, SOC decomposition releases heat, prompting more decomposition and release of CO_2 into the atmosphere (Zhou, et al., 2009). Similarly, dark colored soil, which is associated with high SOC stocks, increases the temperature of the soil, facilitating SOC decomposition. This may mean that soils that appear to have high rates of SOC sequestration may actually have low rates of SOC sequestration (Zhou, et al., 2009). Beyond temperature, moisture plays a role in SOC sequestration. Increased SOC increases water retention, prompting SOC decomposition and release into the atmosphere (Zhou, et al., 2009). Taking temperature and moisture together, well-drained soils in cooler climates have the most potential for SOC sequestration.

Intrinsic SOC molecular properties

Many scientists conclude that the above ecosystem properties are the best way to predict and explain rates of SOC sequestration. Molecular structure of biomass is not a reliable predictor of SOC persistence because studies have shown that lignin, which is thought of as a recalcitrant carbon compound, can turnover more rapidly than other molecules, such as sugars, which are thought to be labile carbon compounds (Schmidt, et al., 2011). In sum, we cannot extrapolate the turnover rate of compounds in fresh litter to determine the persistence of these compounds in the long term (Schmidt, et al., 2011). This could be because SOC molecules rely on particular enzymes to break down or because microbes cannot come in contact with the compounds due to heterogeneity in soil conditions (Carol Adair, et al., 2009, Schmidt, et al., 2011).

Although much research exists on the importance of ecosystem properties in determining the rate of SOC sequestration and persistence, a minority concludes that there are intrinsic molecular properties that make SOC recalcitrant or labile (see Figure 1). For instance, a study on seagrass restoration found that SOC sequestration rates depended on the type of sediment in which the seagrass grew and that the amount of sequestered SOC depended on sediment characteristics (Grenier et al., 2013). On one hand, recalcitrant SOC, or SOC that decomposes very slowly and is therefore good at sequestering SOC, has a high clay and silt content and strong aggregates that physically protect it from decomposition by microorganisms (Schmidt, et al., 2011). In an analysis of large-scale soils maps, soils with high clay content were found to be more recalcitrant and thus better predictors of SOC stocks than climate (Mueller and Koegel-Knabner, 2009). Labile SOC, on the other hand, often has a higher porosity, which increases bioturbation and soil aeration, moving CO_2 from soil into the atmosphere (Conant, et al., 2008). In addition, large-scale soils maps use parent material to categorize soils because it has been found as a strong predictor of SOC sequestration potential (Zhou, et al., 2009). These findings contradict Schmidt et al. (2011) who concluded that ecosystem properties better explain rates of SOC sequestration than molecular properties do. The contradictions between findings suggest that more research should be conducted on the characteristics of SOM and SOC that affect rates of SOC sequestration.

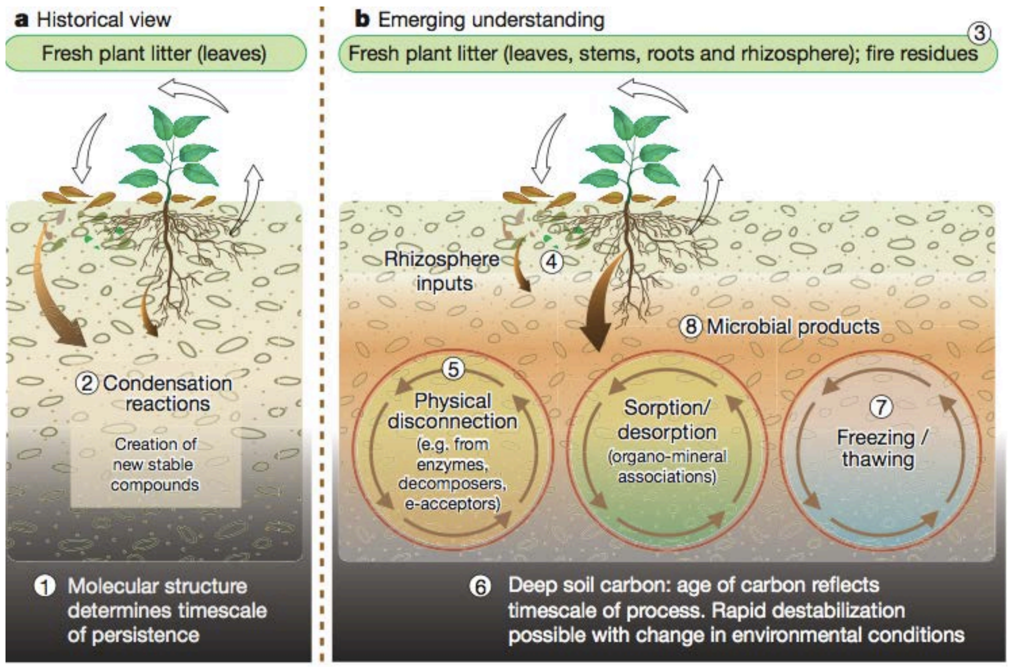

Figure 1: ***Summary of conflicting views of factors that influence SOC sequestration.*** *Historically, SOC sequestration was seen as a function of molecular properties only (a). There is now evidence that ecosystem properties (b) influence rates of SOC sequestration (Schmidt, et al., 2011).*

SOC sequestration of ecosystems in their equilibrium state

Although it is not fully known what molecular or ecosystem properties control rates of SOC sequestration, there is some evidence that SOC sequestration rates stabilize over time as a system reaches equilibrium (Guo and Gifford, 2002, Schmidt, et al., 2011). The most frequently agreed upon timeframe for equilibrium and a stable rate of SOC sequestration is 20 to 30 years after a land-use change (Trumbore, 2000, van Wesemael, et al., 2011). In general, the equilibrium rate of SOC sequestration increases in proportion to SOM input, but eventually, the soil is saturated—despite increased SOM input, sequestered SOC does not increase (Zhou, et al., 2009). In other words, there is a maximum rate and value of SOC for a given soil, limiting the potential for terrestrial SOC sequestration (van Wesemael, et al., 2011, Zhou, et al., 2009).

Other studies question the validity of the existence of a stable, equilibrium rate of SOC sequestration. Throughout the year and from year to year, there are variations in 14C, an indicator of SOC, in boreal, temperate, and tropical forests (Trumbore, 2000). SOC fluctuates on a daily basis, likely as a result of temperature and moisture regimes, showing the importance of ecosystem factors in analyzing SOC and the SOC sequestration potential of a given soil (Carol Adair, et al., 2009). These studies question the existence of ecosystem equilibrium: If an ecosystem is always changing, how can a rate of SOC sequestration ever be stable? Without a consensus on the existence of a stable rate of SOC sequestration, it is clear that more research needs to be done to understand and calculate rates of SOC sequestration.

Land-use change sets SOC sequestration rates out of equilibrium

Numerous studies on the effects of specific land-use changes to specific soils in specific locations exist, but there is no unifying explanation for the effects of land-use changes on the rates of SOC sequestration. In a meta-analysis of rates of SOC sequestration after a land use change, Guo and Gifford (2002) found that changes from pasture to plantation, from native forest to plantation, from forest to crop, and from pasture to crop decrease SOM and SOC (Figure 2). The reverse of these processes increased SOC sequestration. However, these results were generalized from 537 studies, and upon closer examination of specific research, it is clear that some research contradicts these conclusions, making generalizations misinforming (Schmidt, et al., 2011). Because most research has focused on changes from agricultural land to forest or restored prairie, and vice versa, and because this land-use change is of particular relevance to Carleton College, we looked more closely at the effects of changes from forest and prairie to agricultural land, and vice versa, on SOC sequestration.

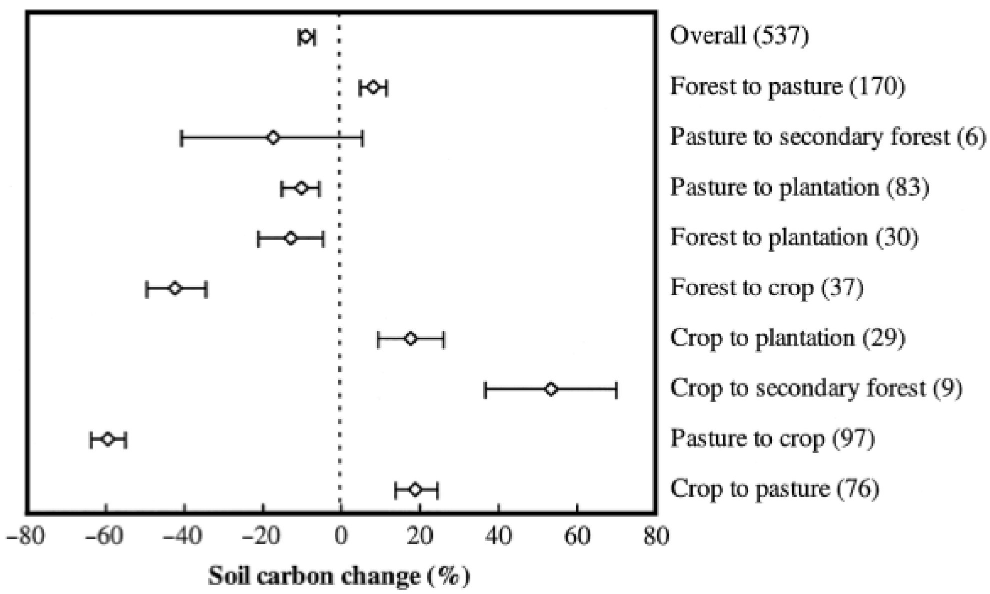

Figure2: ***Summary of effects of specific land-use changes on SOC sequestration.*** *Guo and Gifford (2002) averaged the results of 537 studies on the effects of a given land-use change on SOC stocks. Of interest to Carleton is crop to pasture and crop to secondary forest, both of which, on average increased SOC by 20 percent and 50 percent, respectively.*

Agricultural conversion results in a net loss of SOC. Larger SOC stocks exist under forest and grassland as compared to cropped land, so it follows that turning forest and grassland into agricultural land reduces SOC stocks (Schmidt, et al., 2011). Furthermore, SOC is lost when forests and grasslands are turned into agricultural land because SOM decreases when vegetation is removed. The largest single terrestrial cause of CO_2 emissions is deforestation for cropland (Schulp, et al., 2013).

Because SOM and SOC are lost when forest is turned into agricultural land, it follows that afforestation increases rates of SOC sequestration immediately following a land-use change (Schmidt, et al., 2011, Trumbore, 2000, Zhou, et al., 2009). Specifically, Post and Kwon (2000) found that in the long term, SOC becomes sequestered more deeply in the soil, and as a system returns to equilibrium after being restored from agricultural land, it becomes more productive. Therefore, SOC sequestration rates increase after restoration to grassland or forest.

However, some studies reveal that afforestation and grassland restoration are ultimately unsuccessful. In contradiction to Post and Kwon (2000), Schulp et al., (2013) found that SOC stocks can be regained after afforestation, but the rate of SOC sequestration is much slower than the loss from deforestation. In addition, rates of carbon and nitrogen accumulation in a restored prairie decreased with restoration age, suggesting that there is a rapid increase in SOC and nitrogen after conversion and a slow decline thereafter. This might be explained by the vegetation that dominates a primary succession (annual grasses) versus a secondary succession (perennial grasses) (Hernandez, et al., 2013). Therefore, looking at the rates of SOC sequestration immediately after a land-use change is misinforming. When these rates are used to project rates of SOC sequestration generally, they are an overestimate and make it seem as if afforestation and prairie restoration are more successful than they actually are.

In addition, there are studies that show that rates of SOC sequestration fluctuate as a function of precipitation and SOM rather than as a function of a given land use. In areas with 2000-3000mm of annual precipitation, afforestation of grasslands with some trees decreased SOC, whereas in all other climates afforestation increased SOC sequestration.

Based on the climate of Minnesota, afforestation will increase SOC sequestration at Carleton. In addition, afforestation only increased SOC in deciduous forests and had a neutral or negative effect in coniferous forests (Kalbitz, et al., 2000). This is important to keep in mind as Carleton's campus has both deciduous and coniferous vegetation.

There is contradictory research on whether afforestation or restored grassland has a higher rate of SOC sequestration, so it unclear what land-management practice would be best at Carleton. One statistical analysis found that there was no difference in sequestered SOC or in the rate of SOC sequestration between forest and grassland when the more substantial forest organic-horizon was ignored. Although most soil analyses are done to a depth of 30 to 60cm only, there is evidence that SOC stocks do not change below 60cm after afforestation and grassland restoration, revealing that changes to SOC may be attributed to roots and the organic-horizon only (Kalbitz, et al., 2000). Similarly, there is no statistical difference between SOC in mineral soil under forest versus grassland; the difference exists in the SOC content of the organic-horizon only (Schmidt, et al., 2011). Similarly, a comparison of long-term grassland and forest revealed that they had the same amount of sequestered SOC. Furthermore, trees on pasture and plantations reduced SOC stock more than forests (Kalbitz, et al., 2000). To understand whether restoring grasslands or planting more trees would increase SOC sequestration at Carleton more research needs to be conducted on SOC sequestration in general and specifically along the prairie forest boundary of the central Midwest.

Regardless of whether or not a given land use is better at sequestering SOC, it is clear that historic land use is a better predictor of SOC stocks than current land use. Changes to SOC show up decades after a land-use change and last hundreds of years because SOC turns over on a scale of hundreds to thousands of years (Sommer and Bossio, 2014, Zhou, et al., 2009). Although there is no consensus on how long it takes for afforestation of agricultural land to achieve the same rate of SOC sequestration as continual forest—figures range from 40 years to hundreds of years—there is consensus that it takes time (Schmidt, et al., 2011, Trumbore, 2000, Zhou, et al., 2009). For instance, using a computer model, differences between high SOM input systems and low SOM input systems can still be seen after many years, exemplifying SOC sequestration rates are slow and change in SOC stocks is gradual (Zhou, et al., 2009). Similarly, Mueller and Koegel-Knabne (2009) found that decades after afforestation, a restored forest still had lower SOC and SOM than an area that had had continual forest. Therefore, any changes to land-use management made at Carleton will likely have no effects for several decades.

Changes in ecosystem properties associated with land use change

Any land-use change alters ecosystem properties, including vegetation and roots, soil structure, nitrogen input, and microorganisms. Looking at variables that change with afforestation and/or prairie restoration would show what land management changes should be made to increase SOC sequestration. In conducting research for this paper, we could find research only on the effects of a land-use change on vegetation, nitrogen, and soil structure. The lack of information available suggests that more research should be conducted on the effect of specific land-use changes on ecosystem and molecular soil properties.

Vegetation

With a change in land-use often comes a change in vegetation. Vegetation creates an organic-horizon, which is a significant fraction of SOM and therefore, SOC. Adair et al. (2009) found that overall, grasslands cannot sequester as much SOC as forests because they have a quicker SOC turnover rate and have less organic litter. Therefore, it is possible that a diverse forest has the greatest potential for SOC sequestration. Adair et al. (2009) also found that increasing plant diversity consistently increased sequestered SOC even after removing the influence of roots' biomass. A part of vegetation is their root structures that pervade soils. Because roots are a strong influence on carbon flux, particularly in subsoils, they are essential to SOC sequestration. Roots may either prime microbial activity or they may be a net source of input, but current research does not shed light on which of these roles roots play and when (Schmidt, et al., 2011).

Nitrogen

The amount of nitrogen in a soil is tied to a soil's SOC sequestration rate and nitrogen input changes with land-use changes, so research on nitrogen could help find land management practices that increase SOC sequestration. Although terrestrial ecosystems lose SOC when they go from forest or grassland to agricultural land, the increased use of nitrogen in cropped systems may offset the SOC loss (Hernandez, et al., 2013). Nitrogen decomposition catalyzes plant growth, which, in turn, facilitates SOM accumulation, leading to increased SOC sequestration. However, roots may explain the positive effect of nitrogen because increased roots increase nitrogen as well as SOM. When roots are removed from analysis of rates of SOC sequestration after a land-use change, nitrogen had no effect on the rate of sequestration (Carol Adair, et al., 2009). Contrastingly, Kalbitz et al. (2000) found that adding nitrogen fertilizer to fields catalyzed SOC decomposition and, therefore, limited SOC sequestration. Therefore, there is no clear answer as to how nitrogen affects land-use changes, so more research needs to be done in order to understand how nitrogen should be used to increase SOC sequestration.

Soil Structure

Land-use changes alter the structure of soils, often reducing the rate of SOC sequestration. Disturbances, such as tilling and logging, expose soil aggregates to the air. By exposing these aggregates, the carbon that was once physically inhibited from turning over can more easily be mineralized or oxidized (Schmidt, et al., 2011). Disturbance of this nature can also homogenize soil conditions, which increases the rate at which microbes come in contact with carbon compounds, causing them to decompose faster and making them worse as sequestering SOC. However, agricultural practices, such as tilling, compact soil, reducing pore space, which could make aggregates less available to microorganisms, increasing the ability for SOC sequestration (Kalbitz, et al., 2000).

Attempts at modeling SOC sequestration and stocks

To better understand the effects of land-use changes on SOC sequestration and to create land-use management techniques that decrease atmospheric CO_2, it is essential to estimate current SOC stocks and rates of SOC sequestration. Because there is no consensus on what ecosystem properties and what molecular properties influence rates of SOC sequestration, it is difficult to understand the results of studies on land-use changes and it is difficult to create formulas and models to calculate the future potential of SOC sequestration stocks and rates.

Many authors think current models that estimate SOC stocks and dynamics are too simplistic or make incorrect assumptions. For example, Schmidt et al. (2011) found that carbon residence time is a product of the interaction between intrinsic molecular properties and the surrounding ecosystem. Therefore, Schmidt et al. (2011) advocate for biogeochemical models of SOC sequestration and for the sharing of data across different environments and between scientific disciplines. Similarly, Schlup et al. (2013) expressed dissatisfaction with national carbon estimates that are based on current land use only because these models do not account for significant ecosystem properties of SOC sequestration. Likewise the common method of using ^{14}C as an indicator of SOM respiration and then converting the respiration rate to a SOC sequestration rate using a specific formula appears to explain SOC sequestration differences based on climate only (Trumbore, 2000). In general, many current models assume homogeneity of SOC and SOM to estimate turnover times even though SOC and SOM are heterogeneous. Models that assume SOC and SOM homogeneity underestimate the short-term response and overestimate the long-term response of SOC to land-use changes (Trumbore, 2000).

A model that uses molecular and ecosystem properties and that does not oversimplify variables is the new integrated model (Zhou, et al., 2009). This model uses a constant based on the input of organic materials (*h*) and the SOC decomposition rate (*k*) to determine the change in the rate of SOC sequestration over time. The constants *h* and *k* are based on a given climate, given soil characteristics, and specific human activities. The existence of these constants reveals that SOC sequestration rates increase linearly with an increased carbon input. However, it is important to note that there is an asymptote: at a certain point, increased carbon no longer increases SOC sequestration. Based on the literature reviewed in this document, little is known about the factors used to calculate *h* and *k*, so it is unclear how Tan et al. (2014) use their equation. In addition, because this model is new, there is no research that tests its validity. Therefore, more research on SOC models and on this model in particular needs to be conducted before we can understand the effects of changes to rates of SOC sequestration over time.

To create a model that can be used to inform land-use management policies for increased SOC sequestration, countries use Soil Monitoring Networks (SMN). Because soil scientists cannot sample all possible combinations of ecosystem properties, molecular properties, and land uses, they need to collect only enough samples to create regional maps that can be used to make large-scale land-use management policies (Trumbore, 2000). To do this, there needs to be a system for sampling, a timeframe for resampling, and requirements for what to measure and how to measure it. The SMN guidelines are current land-use, management history, climate, comparison with a paired site, and measurements of molecular properties (van Wesemael, et al., 2011). Because so little is known about SOC sequestration properties and rates, it is difficult to know if these are the correct factors to measure and if there are other factors that need to be measured to create accurate SMNs Therefore, more research needs to be done to assess the validity of current variables measured for SMN and to find additional variables that can improve the accuracy of SMN. However, there is a consensus that SMNs do reduce uncertainty about SOC stocks and sequestration rates and that, therefore, they have potential to influence policies that can increase SOC sequestration (van Wesemael, et al., 2011).

Conclusion

Because there are many contradictions among current research on the molecular and ecosystem properties of SOC and on the factors that affect rates of SOC sequestration, more research needs to be done in order to create models that accurately reflect current SOC stocks and their potential for future sequestration. Currently, SOC sequestration rates can only be understood in terms of specific ecosystem properties, specific molecular properties, and specific land-uses. In order to create unifying theories and concepts of the nature of SOC sequestration and the rates at which SOC is sequestered, more research on all aspects of SOC should be conducted. Despite the large gaps and contradictions in current research, it is clear that to increase SOC stocks we must increase the rate of input of organic matter into soil, create more recalcitrant carbon, place SOM deeper in the soil, and enhance physical protection of SOC (Schmidt, et al., 2011). A fuller, more unifying picture of SOC properties and their rates of sequestration will allow us to create models of SOC stocks and sequestration potential. These models could be used to create better land-use management policies at Carleton, as well as on a larger scale.

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