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Natural Asset Carbon Assessment Guide and Toolbox

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Preface:

This Guide and Toolbox is intended to help Conservation Authorities and their municipal partners better inform and coordinate climate change mitigation strategies. It achieves this by providing guidance to standardize the use of tools, methods, and resources for estimating carbon sequestration and storage by natural assets within Southern Ontario.

Executive Summary

Nature-based solutions to growing climate change concerns and rapid urbanization challenges are becoming popular in Southern Ontario, Canada. Notably, there is growing interest in the carbon sequestration and storage services provided by natural assets and their potential to help mitigate the impacts of climate change.

Exploring the role of natural assets in mitigating the effects of climate change requires estimating how much carbon these assets can sequester and store. A variety of tools, methods, and resources have been developed for this purpose. However, as the library of available tools increases, so does the variation in carbon sequestration and storage estimates they produce, as does the probability of utilizing a tool incorrectly or using the wrong tool. This may lead to a loss of confidence in the reliability and accuracy of the tools and the estimates they produce.

In response, Credit Valley Conservation, Toronto and Region Conservation Authority, and Lake Simcoe Region Conservation Authority have developed the Natural Assets Carbon Assessment Guide and Toolbox to guide the correct use of methods, tools, and resources to standardize carbon sequestration and storage estimations across Greater Toronto Area and Lake Simcoe Region. This Guide and Toolbox includes: 1) a brief introduction to the carbon cycle and important information regarding carbon assessments, 2) a table of locally applicable land cover types-based carbon sequestration and storage rates to conduct a baseline assessment across a landscape, and 3) guidance on the use of both internally-developed and publicly-accessible tools and resources applicable to different natural assets, spatial scales, and project objectives.

By standardizing carbon assessments, this Guide and Toolbox is intended to help Conservation Authorities and their municipal partners better inform and coordinate climate change mitigation strategies. By building a stronger case for protecting, managing, and restoring natural assets, the guide will also help these organizations to enhance their climate change adaptation capacity.

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Section 1: Introduction to the Guide and Toolbox

Background

Natural Assets and the Carbon Cycle

Natural assets (e.g. trees, forests, wetlands, grasslands, and manicured open spaces) provide a variety of **ecosystem services**, including the removal, or sequestration and storage of carbon from the atmosphere (e.g. accumulated in living biomass, litter, deadwood, and soil and harvested lumber). **Carbon sequestration and storage** counter the emission of carbon from natural (e.g. respiration, decomposition) and human sources (e.g. deforestation, land use, land cover change, industrial emissions) as part of the **carbon cycle**[1] (Figure 1). The carbon cycle is the global **exchange, or flux, of carbon** between terrestrial, aquatic, and atmospheric stocks. In light of increasing human-caused emissions, carbon sequestration and storage services by natural assets help mitigate the effects of **greenhouse gas (GHG)** emissions (e.g. **global warming**) and **climate change**.

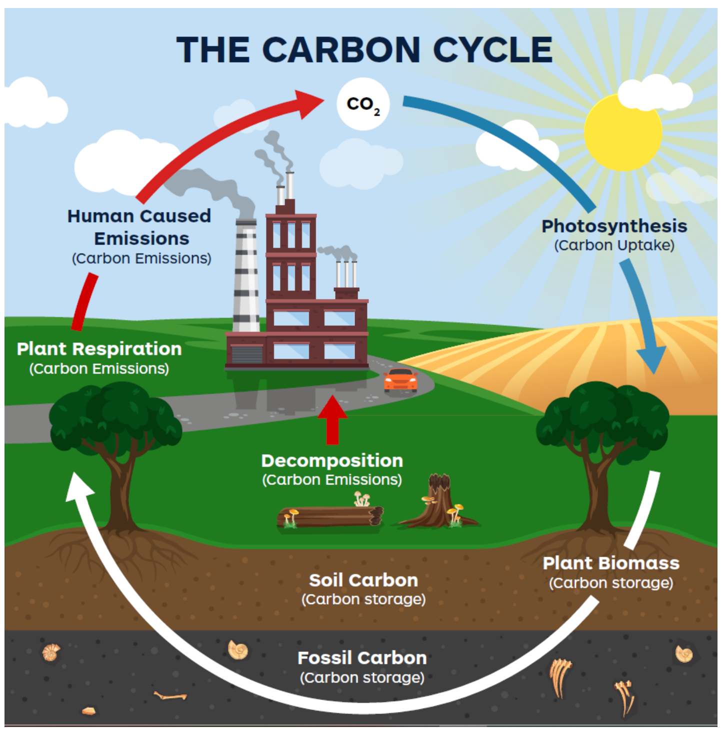

Figure 1. A simplified representation of part of the carbon cycle. Note that aquatic systems and other living organisms also contribute to carbon exchange but are not included in this image. Image credit: CVC.

Factors that Influence Carbon Sequestration and Storage

Carbon sequestration and storage are not static processes. Generally, carbon balances fluctuate daily with photosynthesis. Plants uptake carbon during the day and respire carbon dioxide (CO_2) at night. These

[1] See Chapter 7.3: The Carbon Cycle and the Climate System by the IPCC for more background information about the carbon cycle. https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch7s7-3.html

processes also fluctuate seasonally with periods of growth in the spring and summer and dormancy in the autumn and winter (Randerson et al. 1999, Coursolle et al. 2012). Carbon sequestration and storage also change over the life cycle of vegetation, with higher rates of sequestration occurring at younger ages and plateauing or decreasing at older ages as growth slows and carbon becomes stored in biomass.

Multiple environmental factors affect carbon sequestration and storage. Carbon stores vary naturally based on soil type and texture and across ecozones (Congreves et al. 2014). Altitude also plays a role, where higher elevations are associated with lower sequestration and storage due to reduced vegetation growth (Fajardo et al. 2013). Environmental processes and catastrophes can also impact carbon stocks. For instance, forest fires release stored carbon into the atmosphere as CO_2, while extreme weather events may damage natural assets and impair their ability to sequester and store carbon.

Although climate change may reduce the capacity of natural assets to sequester and store carbon in the future, the interaction between climatic factors and their effects on the carbon cycle is complex. For example, increasing temperatures and concentrations of CO_2 and ozone (O_3) may initially promote vegetation growth and sequestration due to longer growing seasons. However, as soil nutrient stocks are depleted, the carbon sequestration capacities of forests will decline (Hui et al. 2015). At the same time, if nutrients are not limited (e.g. increased fertilization) and precipitation increases, growth and carbon sequestration rates may remain elevated (Hui et al. 2015). More complicated still, longer growing seasons will increase the duration of carbon release from soil respiration and decomposition of organic matter each year, especially at higher latitudes where permafrost is thawing (Randerson et al. 1999). Therefore, climate change will generally negatively impact soil carbon stocks. These declines in carbon sequestration will be accentuated in drought scenarios, which will become more common with climate change. This is because drought limits vegetation growth and increases the risk and frequency of fires in some regions (Goetz et al. 2007, Hui et al. 2015).

Human activities have impacted all aspects of the carbon cycle. Humans have increased global concentrations of GHGs like CO_2 to levels well above historical records[2], which may influence the capacity of natural assets to sequester and store carbon. Human activities that physically alter or destroy natural assets (e.g. urbanization, deforestation, and the introduction of pests and invasive species) also reduce the capacity of natural assets to sequester and store carbon, especially if keystone species are removed or severely impacted (Birdsey et al. 2006, Boyd et al. 2013). In some instances, invasive species may benefit carbon stocks in the short term[3], especially when there is low water stress and a variety of vegetation heights (Martin et al. 2017). However, this will likely diminish stocks in the long term as invasive species impact the integrity of natural assets in other ways, including by altering nutrient cycling, reducing resilience to catastrophic events, and diminishing habitat quality (Lambert et al. 2010, Boyd et al. 2013, Martin et al. 2017). Actively protecting and managing the health of naturalized landscapes by controlling invasive species and promoting species diversity can help natural assets retain or improve their carbon sequestration and storage capacities (Jandl et al. 2007, Boyd et al. 2013, Martin et al. 2017, Xu et al. 2020).

The Rising Need for Standardized Carbon Accounting

The development of climate change action plans and strategies is on the rise. The value of natural assets and their services is increasingly recognized as essential to mitigate the impacts of climate change and

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[2] See projections of CO_2 concentrations from the IPCC: https://www.ipcc-data.org/observ/ddc_co2.html

[3]See Marshes Dominated by Phragmites australis (European Reed) below (Section 2, page 8) as an example

achieve **net zero or net negative** targets. Municipalities are committing to developing climate change adaptation and mitigation strategies[4] and are working to improve plans for the maintenance and management of natural assets[5]. Given this investment, developing a standardized guide to accurately estimate current and future carbon sequestration, storage, and flux by natural assets is critical. This guide and toolbox will help establish consistent protocols for measuring carbon sequestration and storage, to uniformly document regional carbon benefits from the management of natural assets over time.

Credit Valley Conservation (CVC), Toronto and Region Conservation Authority (TRCA), Lake Simcoe Region Conservation Authority (LSRCA), and other conservation authorities are at the forefront of ecosystem services and natural asset research. Conservation Authorities are regularly developing, applying, and testing relevant methodologies and tools, striving to remain on the leading edge of climate mitigation and adaptation strategies and practices. This has provided a prime opportunity for collaboration among these organizations to develop this guide and toolbox.

Purpose of Creating the Guide and Toolbox

CVC, TRCA, and LSRCA are collaborating to standardize carbon sequestration and storage estimation for several reasons. First, the Greater Toronto Area (GTA) and Lake Simcoe watershed are rapidly urbanizing, and inquiries from internal and external partners about the amount and value of carbon sequestered and stored by natural assets are becoming more frequent. This reflects an interest in both mitigating carbon emissions[6] and making a business case for protecting, managing, and restoring natural assets[7,8]. Second, accurate estimations of carbon sequestration will inform plans for natural heritage systems, to help mitigate the impact of emissions on climate change.

These Conservation Authorities have been developing internal tools and methods as well as using publicly available tools (e.g. i-Tree, National Tree Benefit Calculator, and Urban Tree Database) to address these requests. However, as the library of available tools grows, the variability in carbon sequestration and storage estimates produced by these tools also grows. Estimates may vary due to errors resulting from incorrect tool use or disparities between methodologies due to reliance on different base models. This

[4] The Peel Climate Change Partnership aims to work with local municipalities to "be a leader in the community to reduce greenhouse gas (GHG) emissions and to ensure its services, operations, and infrastructure are resilient to the impacts of climate change." See https://peelregion.ca/climate-energy/#action for more information. The York Region Climate Change Action Plan similarly "addresses climate mitigation and adaptation from a corporate and community perspective."

[5]Ontario Regulation 588/17 under the *Infrastructure for Jobs and Prosperity Act* (2015) requires that Ontario municipalities have asset management plans in place by July 1, 2024, including those for natural assets (Government of Ontario, 2020).

[6]An interest in mitigating carbon emissions has popularized **carbon accounting** to support work towards "net zero or net negative communities" and for **carbon offsetting**. This has also facilitated the growth of the consumer carbon mitigation market (e.g. see Tree Canada, Bluesource, Gold Standard).

[7]Although existing mature natural assets will not increase net carbon sequestration or storage, protecting these assets from land-use change is important as this prevents emissions of carbon dioxide and other greenhouse gases as a result of vegetation loss and soil disturbance (i.e. avoided conversion). Pairing protection with active management and restoration of these assets (e.g. through planting vegetation, controlling pests and diseases) will increase the rate of carbon sequestration.

[8] Rising interest in making a business case for protecting natural assets is also reflected in the recent development of tools, including the Business Case for Natural Assets (BC4NA), Risk and Return on Investment Tool (RROIT), the Low Impact Development Treatment Train Tool (LIDTTT), and System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN).

brings into question the reliability and accuracy of the estimates and may reduce confidence in these tools and their outcomes. Furthermore, the number of empirical studies on landscape-scale carbon storage and sequestration by different land cover types is also increasing. It is, therefore, imperative to detail the tools most applicable to each local climate and land cover type in CVC, TRCA, and LSRCA's jurisdictions.

Objectives of the Guide and Toolbox

The overarching goal of this guide is to provide Conservation Authorities and their partners with consistent and reliable guidance and resources for estimating carbon sequestration and storage. The specific objectives of this guide and toolbox are as follows:

1) Provide locally relevant, per area, carbon sequestration and storage rates and additional information required to conduct assessments of carbon storage and sequestration for various land cover types, and
2) Provide guidance regarding which tools, methods, and resources should be used to estimate carbon sequestration and storage for different natural assets (e.g., wetlands vs. grasslands), spatial scales (e.g. individual trees, forest stands, and patches of forest across a landscape), and project objectives and scenarios (e.g. restoration projects or protecting existing forests).

How to Use the Guide and Toolbox

This guide and toolbox are organized into two parts. Section 2 provides a summary of annual carbon storage and sequestration rates for local land cover types, including forests, wetlands, grasslands, and manicured open spaces. These rates can inform quick baseline estimations of carbon storage and sequestration across a landscape or be input into detailed analyses using the tools and methods described in Section 3.

Section 3 provides an overview of the various tools and methods available for estimating carbon storage and sequestration. Tools for assessing different types of natural assets ranging from local scale (i.e. individual trees) to landscape-level (i.e. land cover types) are described. Guidance on how and when to use specific tools and methods is also outlined in this section (Tables 2 and 3).

Appendix A and B contain supplementary information about carbon storage and sequestration for different land cover types. Appendix A summarizes the methodology used to compile the rates for each land cover type in Table 1. Appendix B provides additional carbon storage and sequestration figures not included in Table 1.

Equating Measurements of Carbon to other Greenhouse Gases and Emissions Metrics

In some cases, GHG equivalency or conversion may be required for additional calculations or communication of results. For example, emission reduction targets are often communicated as tonnes of carbon dioxide equivalent (CO_2e). This metric is achieved by multiplying the total amount of carbon (in tonnes) by a factor of 3.67, the relative molar mass of CO_2. Depending on the audience, presenting a relatable statistic, such as the equivalent emissions in the number of passenger vehicles, may be preferred[9].

The Importance of Natural Assets Beyond Carbon Storage and Sequestration

Carbon storage and sequestration are only two of the many services that natural assets provide. This should be kept in mind when interpreting data or tool outputs below. If a natural asset provides minimal carbon storage and sequestration, it should not be discounted, or perceived as having lesser value. The asset likely provides other important and complex ecosystem services that are outside the scope of this guide.

Disclaimer and Updates to the Guide and Toolbox

CVC, TRCA, and LSRCA hope to keep this guide up to date with periodic updates on carbon storage and sequestration research, tools, and methods. This is the first version of the guide and, as such, does not provide a comprehensive list of all the tools and methods available. Additional tools and techniques will be added in future versions.

[9] The "Greenhouse Gas Equivalencies Calculator", provided by Natural Resources Canada, converts tonnes of carbon to relatable statistics: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/calculator/ghg-calculator.cfm.

Section 2: Carbon Sequestration and Storage Rates by Land Cover Type

The growing interest in carbon accounting across landscapes has highlighted the need for reliable carbon storage and sequestration assessments. This need can be addressed by creating a standardized and locally relevant database of carbon rates based on empirical studies from the scientific literature. Rates are presented for the following land cover types: forest, grassland, wetland, and manicured open space[10].

To compile a carbon sequestration and storage rate database, the authors reviewed The International Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (Paustian et al. 2006). The authors also consulted over 50 scientific publications that reported rates applicable to the land cover types across CVC's, TRCA's, and LSRCA's jurisdictions. Most publications were based in Ontario and conducted within the last 20 years. Studies outside of Ontario were focused on similar species, environments, and climates (e.g. Michigan, Pennsylvania).

The database (Table 1) includes a description of the land cover type, a net carbon sequestration rate, a soil organic carbon (SOC) storage rate, information about sources, and a Confidence Ranking, as described below. The first four columns of the table describe the land cover type(s) in various ways [including use of **Ecological Land Classification** (ELC) codes; see CVC 1998 for descriptions] to help identify land cover types suitable for the application of carbon sequestration and storage rates. Note that the table reports net rates (i.e. carbon sequestration minus emissions from the respiration of vegetation) to provide a more realistic account of carbon sequestration and storage for practical applications.

Carbon sequestration can be measured as **net primary production (NPP)** or **net ecosystem production (NEP)**. NPP estimates annual biomass production, represented by net carbon uptake by vegetation only. This usually includes losses from respiration, litterfall, biomass turnover, disturbances, and sometimes harvesting. NEP, on the other hand, accounts for the net carbon exchange between terrestrial ecosystems (NPP plus losses from decomposition) and the atmosphere (see p. 268 of CBM-CFS3 User Guide and Chen et al. 2003). Therefore, NPP likely underestimates the total carbon sequestration of an ecosystem. A more detailed breakdown of carbon sequestration and storage information for each land cover type can be found in Appendix B.

The information in the database should be used to establish an annual baseline for carbon storage and sequestration across a landscape. It can also be used as input for the tools and methods described in Section 3. However, it should not replace detailed modelling or methodologies that estimate carbon sequestration and storage by the tools and methods described in Section 3.

To illustrate the certainty in the relevance of these rates to local jurisdictions, the table includes a "Confidence Ranking." The confidence in applying these rates is ranked as Low, Medium, or High and a rationale to explain each ranking is provided. Several variables contributed to the confidence ranking, including the location of study (more applicable if in southern Ontario), the date of study (more applicable if recent), the vegetation community/ ecozone/ climate (more applicable if similar to those in southern Ontario), and support from similar studies (not an outlier when compared to empirical studies in other locations). The literature review yielded net carbon sequestration and storage rates that were believed to be locally applicable, current, and well-supported, negating the need to present rates with a low confidence ranking in the main table.

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[10] See the subsection below and Appendix A and B for additional details and specific considerations for land cover types.

Important Considerations about Carbon Sequestration and Storage for Specific Land Cover Types

Agricultural Lands

The high variability in carbon sequestration and storage rates reported for agricultural land cover types has precluded its distillation into a single representative rate. However, the document provides recommendations for improving carbon sequestration and the overall sustainability of agricultural land cover. Those are described below. Please see Appendix A for other important considerations.

It is challenging to identify clear trends in carbon sequestration and storage from agriculture because agricultural practices and environmental factors create variability in carbon measurements. Generally, the changing state of agricultural land cover throughout the year (i.e. periods of fertilization, plowing, harvest, etc.) makes it challenging to specify a single annual sequestration and storage rate (e.g. about 50% of carbon is removed from agricultural lands during the harvest; Ogilvie 2021). Different farming practices, such as tillage and crop rotation, also impact the sequestration and storage of carbon in crops and soils (Congreves et al. 2014). Soil types, textures, and ecozones influence soil organic carbon (SOC) stocks. Variability in soil texture and drainage may explain why a study comparing the effects of crop rotation on SOC at 40 cm found higher carbon sequestration in some locations (up to 1.03 t C/ha/yr) and lower sequestration in others (down to -1.54 t C/ha/yr; Congreves et al. 2014).

Fortunately, reporting local environmental factors is becoming standard practice for carbon accounting from agricultural lands. For example, ecozones and soil textures were included in the carbon reporting protocol recently published in a guide by the Climate Action Reserve to facilitate the reporting of GHGs from the avoided conversion of grasslands in Western Canada[11]. This should improve the interpretation of carbon accounts from agricultural land cover in the future.

Intensive agriculture can be a net emitter of GHGs, but recent research suggests that certain agricultural practices may reduce GHG emissions and improve sustainability if consistently practiced over the long term. These sustainable practices also benefit crop yields, stability, and resilience to adverse environmental conditions and climate change[12]. These practices include:

- Rotating crops (e.g., with alfalfa, winter wheat, or red clover),

[11] The Canada Grassland Project Protocol aims to "account for, report, and verify greenhouse gas (GHG) emission reductions associated with projects that avoid the loss of soil carbon due to conversion of grasslands to cropland, as well as other associated GHG emissions. This protocol was designed to ensure the complete, consistent, transparent, accurate, and conservative quantification and verification of GHG emission reductions associated with an avoided grassland conversion project." The protocol can be accessed here: https://www.climateactionreserve.org/wp-content/uploads/2020/12/Canada_Grassland_Project_Protocol_V1.0_Package_121819.pdf

[12] See Meyer-Aurich et al. (2006), Van Eerd et al. (2014), Congreves et al. (2014), Congreves et al. (2017), Jarecki et al. (2018), Chahal et al (2020), and Morrison and Lawley (2021) for more information about sustainable agricultural practices recommended above. Not for profit organizations including Soils at Guelph (https://soilsatguelph.ca/), Farmers for Climate Solutions (https://farmersforclimatesolutions.ca/), Ontario Soil Network (https://ontariosoil.net/), and the Canadian Forage and Grassland Association (https://www.canadianfga.ca/) are also working with farmers to promote sustainable farming practices.

- Including diverse cover crops (e.g. winter wheat, oilseed radish, oat, rye) in a crop rotation, which improves overall soil health, including soil carbon and nitrogen storage[13],
- Including perennial crops in rotation, which have living roots and thus improve carbon sequestration, storage, and nitrogen fixation (reducing the need for fertilizer),
- Strategic tilling (e.g., reduced tilling, or shallow tilling), allowing the nitrogen and carbon-fixing microbes in the soil to persist and maintaining root systems from previous crops (Ogilvie 2021, M. Oelbermann pers. comm.),
- Increasing plant diversity in pastures (Xu et al. 2020),
- Managing grazing in pastures (see Rathgeber 2021[14]), and
- Promoting agroforestry, shelterbelts, and hedgerows (Fraser and Bork 2021, M. Oelbermann pers. comm.).

Educating farmers and working with farming communities is critical for promoting and successfully implementing these practices[15].

Forest

The sequestration and storage of carbon in forests are complex, and therefore, studies often note a variety of additional measurements. These measurements were noted in Appendix B when reported, including additional information about storage and sequestration in trees and saplings, understorey vegetation, roots, deadwood, leaf litter, general above- and below-ground accounts. Please note that "treed swamps" are not included as forests but are listed under the wetlands land cover type.

A conservative approach was used to document carbon sequestration rates for forests. Above-ground net primary production (ANPP) in tonnes of carbon per hectare per year (t C/ha/yr) was reported as a measure of carbon sequestration (refer to Section 2 above), which was the most reported carbon sequestration metric for forests. If another measure of carbon sequestration was reported, this was noted in the table.

Wetlands

Wetlands are unique in their capacity to store carbon compared to other land cover types. Like other land cover types, wetlands store carbon above-ground in vegetation and below-ground in soils and decaying biomass. However, their soils' high moisture and organic matter content create an anoxic environment, thus slowing the decomposition of organic material. These conditions favour long-term carbon storage. Wetland carbon storage capacity depends on wetland type (i.e., bog, fen, marsh, swamp), size, vegetation, the amount of organic soil, groundwater, nutrient levels, pH, and other environmental factors.

Although wetlands naturally release carbon through respiration and decomposition, like other land cover types, the destruction of wetlands by humans is concerning because large stocks of carbon dioxide (CO_2) and more potent gases like methane (CH_4) and nitrous oxide (N_2O) are released. Wetlands should be

[13] The 2020 Ontario Cover Crop Feedback Report suggests that soil health and increased organic matter in soil are the main reasons that farmers will plant cover crops. Benefits after planting cover crops were noticed by farmers within a year.

[14] Rathgeber 2021: Forage Best Management Practices for Enhancing Soil Organic Carbon Sequestration https://www.canadianfga.ca/uploads/source/BMP-Manual.pdf

[15] See the subsection below and Appendix A and B for additional details and specific considerations for land cover types.

protected since it will take decades for a newly established or restored wetland to become a GHG sink. Wetlands, and their carbon stores, can be protected by reducing:

- Wetland drainage and other land and water management practices that lead to dewatering of wetlands,
- Fires in wetlands (especially in cases of prolonged drought), and
- Peat harvesting and other similar intrusive practices.

Marshes Dominated by Phragmites australis (European Reed)

Marshes dominated by *Phragmites australis* (European Reed) sequester high amounts of carbon per hectare (8.81 t C/ha/yr; Pendea, 2019) but including these marshes in carbon sequestration and storage estimations should be critically considered. Studies suggest that invasive species may increase carbon sequestration and storage in the short term but tend to have negative impacts in the long term as they diminish the integrity of the ecosystem (Boyd et al. 2013, Martin et al. 2017). Being notably pervasive, European Reed often dominates plant communities after invasion and negatively impacts the ecosystem's critical structure and functions like habitat quality, nutrient cycling, and sedimentation (Lambert et al. 2010).

Standardizing Measurements of Soil Carbon

Standardizing the depth of carbon measurements in soils is becoming increasingly important for reliable and comparable carbon accounting. Congreves et al. (2014) noted the variability in depth used while measuring carbon in soils (ranging from 10-120 cm). If feasible, soil carbon should be measured below a depth of 30 cm to provide a better account of carbon stock. However, if not feasible, measurements in 15 cm depth increments up to 30 cm can capture dynamic changes in soil health on a short-term basis (Fraser and Bork 2021, M. Oelbermann pers. comm.).

Database for Land Cover-based Carbon Storage and Sequestration Rates

Table 1. Carbon storage and sequestration rates by ELC land cover type. Note that aboveground net primary production (ANPP) is provided as a net carbon sequestration rate for all forest land cover types, unless otherwise stated.

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Open Space	Manicured Lawn	OS, MOS, MOI, MOC, MOO, MOP, MOR	*Poa pratensis* (Kentucky Bluegrass) Establishment up to 25 years old	**1.46**	**N/A**	average of rates from Selhorst and Lal (2013); Zirkle et al. (2011); Qian and Follett (2002)	Wooster, Ohio, USA; USA-wide; Delaware, Ohio, USA	High	In these studies, management practices, growing conditions, and species (i.e. *Poa pratensis*) are similar to those implemented for manicured lawns in Ontario. Rates are thus directly transferable and relevant to Ontario landscapes.
Open Space	Manicured Lawn	OS, MOS, MOI, MOC, MOO, MOP, MOR	*Poa pratensis* (Kentucky Bluegrass) >25 years old	**-0.03**	**56.9 [15]***	average of rates from Selhorst and Lal (2013); Zirkle et al. (2011); Qian et al. (2003); Singh (2007)	Wooster, Ohio, USA; USA-wide; Delaware, Ohio, USA; Delaware, Ohio, USA	High	In these studies, management practices, growing conditions, and species (i.e. *Poa pratensis*) are similar to those implemented for manicured lawns in Ontario. Rates are thus directly transferable and relevant to Ontario landscapes.

*value from Selhorst and Lal (2013)

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Forest	Deciduous	FOD	Mature (based on data from a 53-year-old Trembling Aspen forest)	**2.49**	**97.2 [70]**	Gower et al. (1997)	Manitoba, Ontario, Canada	Medium	Data is not from Ontario, so environmental/ climatic conditions may differ from those in Ontario. The study is also outdated. However, these tree species are typical in Ontario.
Forest	Deciduous	FOD	Mature (based on data from a 90-year-old Red oak, Sugar Maple, Red Maple, Large-tooth Aspen forest)	**1.5**	**-**	Gough et al. (2013)	Michigan, USA	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. However, these tree species are typical in Ontario.
Forest	Deciduous	FOD	Mature (based on data from a 70-110-year-old White Oak, Sugar Maple, Red Maple, American Beech forest)	**2.06** (net ecosystem production)	**-**	Beamesderfer et al. (2020)	Turkey Point, Ontario, Canada	Medium	Data is local, and the study is recent. However, NEP was estimated.

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Forest	Deciduous	FOD	Old Growth (based on data from an 80-120-year-old Maple, American Beech forest, with <60% of trees over 80 years old)	**0.69** (net forest ecosystem carbon stocks)	**103.1 [100]**	Dugan et al. (2018)	Pennsylvania National Forest, USA	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. However, these tree species are typical in Ontario forest communities. Net forest ecosystem carbon stocks (not ANPP) were estimated.
Forest	Deciduous	FOD	Old Growth (based on data from a 70-130-year-old White Oak, Sugar Maple, Red Maple, American Beech forest, with <60% of trees over 90 years old)	**0.16** (net forest ecosystem carbon stocks)	**97.7 [100]**	Dugan et al. (2018)	Pennsylvania State Forest, USA	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. However, these tree species are typical in Ontario forest communities. Net forest ecosystem carbon stocks (not ANPP) were estimated.
Forest	Mixed	FOM	Young (based on data from 25-27-year-old mix wood stands)	**3.7**	**48.2 [60]**	Payne et al. (2019)	Timmins, Ontario, USA	High	Data is local and recent. ANPP was estimated.
Forest	Mixed	FOM	Mature (based on data from 74-81-year-old mix wood stands)	**2.63**	**52.5 [60]**	Payne et al. (2019)	Timmins, Ontario, USA	High	Data is local and recent. ANPP was estimated.

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Forest	Coniferous	FOC	Young (based on data from a 27-year-old Jack Pine forest)	**0.51**	**14.2 [70]**	Gower et al. (1997)	Manitoba, Canada	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. Jack Pine is also not common in Ontario but is similar to Red Pine. The study is also outdated.
Forest	Coniferous	FOC	Mature (based on data from a 63-year-old Jack Pine forest)	**0.98**	**28.43 [70]**	Gower et al. (1997)	Manitoba, Canada	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. Jack Pine is also not common in Ontario but is similar to Red Pine. The study is also outdated.
Forest	Coniferous	FOC	Old Growth (based on data from a 155-year-old Black Spruce forest)	**1.11**	**418.36 [70]**	Gower et al. (1997)	Manitoba, Canada	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. Black Spruce is no longer planted in plantations but is similar to White Spruce. The study is also outdated.
Forest	Deciduous Plantation	CUP1/CUS	Mature Reforested from agriculture (based on data from 53-year-old Tulip Tree and Black Walnut Forests)	**2.36** (ecosystem carbon stores)	**70.2 [100]**	Morris et al. (2007)	Cass County, Michigan, USA	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. However, these tree species are typical in southern Ontario forest communities. Ecosystem carbon stores (not ANPP) were estimated.

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Forest	Coniferous Plantation	CUP3	Young (based on data from a 12-year-old Black Spruce plantation)	**0.8**	**14.1 [15]**	Hunt et al. (2010)	Beardmore, Ontario, Canada	Medium	Although not local, data is from Ontario. Black Spruce is not common in southern Ontario plantations, but this rate can be applied to White Spruce or White Pine plantations. ANPP was estimated.
Forest	Coniferous Plantation	CUP3	Mature (based on data from a 34-year-old White Pine plantation)	**3.83**	**-**	Peichl et al. (2010) [Kula (2013) for forest ages]	Turkey Point, Ontario, Canada	High	Data is local. ANPP was estimated.
Forest	Coniferous Plantation	CUP3	Mature (based on data from a ~35-year-old Jack Pine plantation)	**3.5**	**12.7 [15]**	Hunt et al. (2010)	Beardmore, Ontario, Canada	Medium	Although not local, data is from Ontario. ANPP was estimated.
Forest	Coniferous Plantation	CUP3	Mature Reforested from agriculture (based on data from 50-year-old Red/ White Pine Plantations)	**2.51** (ecosystem carbon stores)	**64.6 [100]**	Morris et al. (2007)	Cass County, Michigan, USA	Medium	Data is not from Ontario, so the environment and climate may differ from those in Ontario. However, these tree species are typical in Ontario forest communities. Ecosystem carbon stores (not ANPP) were estimated.

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Forest	Coniferous Plantation	CUP3	Mature (based on data from a 69-year-old White Pine plantation)	**4.09**	-	Peichl et al. (2010) [Kula (2013) for forest ages]	Turkey Point, Ontario, Canada	High	Data is local. ANPP was estimated.
Wetland	Bog	BOT	Treed Bog	**1.46**	**3.65 [27]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	Medium	Data is local. The sequestration rate is greater but comparable to other reported rates for bogs. This greater rate may be due to the presence of trees in bogs sampled by Pendea (2019) and the lack of trees in bogs tested in other studies.
Wetland	Fen	FES	Shrub Fen	**2.77**	**0.71 [17]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	Medium	Data is local, but this land cover has not been widely examined in other studies, so the rate was difficult to verify.

**This value represents the annual organic carbon accumulation in soil averaged over 100 years

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Wetland	Marsh	MA	Shallow Marsh	**8.55**	**1.1 [average of 15 & 21]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	High	Data is local, and rates are comparable to those presented in other studies.
Wetland	Marsh	MAM	Meadow Marsh	**4.17**	**1.3 [average of 20 & 16]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	Medium	Data is local, but this land cover has not been widely examined in other studies, so the rate was difficult to verify.
Wetland	Marsh	OA	Open Water	**2.38**	**0.95 [22]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	High	Data is local and comparable to similar land cover rates in other studies.
Wetland	Swamp	SWM	Treed	**2.94**	**0.87 [average of 14 & 18]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	High	Data is local and comparable to similar land cover rates in other studies.

**This value represents the annual organic carbon accumulation in soil averaged over 100 years

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Net Carbon Seq. Rate (t C/ha/yr)	Soil Organic Carbon (t C/ha) [Depth of Soil Measurement (cm)]	Reference(s)	Location(s) of Study/ Measurements	Confidence in Applying this Rate Locally	Reasoning for the Confidence Ranking
Wetland	Swamp	SWT	Thicket	**1.99**	**1.7 [average of 21 & 24]**** (t C/ha/yr)	Pendea (2019)	Lake Simcoe, Ontario, Canada	Medium	Data is local, but this land cover has not been widely examined in other studies, so the rate was difficult to verify.
Grassland	Cultural Meadow/ Perennial Grassland	CUM	Previously annual row crop	**1.08**	**1.0 [100+]***** (t C/ha/yr)	Anderson et al. (2008)	Minnesota, USA	Medium	Similar climate and ecosystem to that in Ontario. The reported value is an average of measurements from 24 studies, but measurements across the studies were highly variable.

**This value represents the annual organic carbon accumulation in soil averaged over 100 years

***This value represents the annual organic carbon accumulation in soil averaged over 50 years.

Section 3: Tools and Methods to Estimate Carbon Sequestration and Storage

There are many tools and methods for estimating carbon sequestration and storage by natural assets, but deciding on the most appropriate tool for a particular application can be challenging. This section describes various common tools and methods and suggests when they should be used. Key considerations include: 1) the type of natural asset, 2) data requirements and availability, and 3) the required precision of carbon estimations. Tables 2 and 3 provide guidance on selecting the most appropriate tools and methods for various tasks. Table 2 indicates which tools are suitable based on the asset type and data requirements, while Table 3 summarizes the outputs provided by each tool.

Deciding on a Tool or Method

In Table 2, asset types are segregated into columns while rows depict various data requirements. To use the table, find the asset type of interest in the top row and then select the data required in the left column. The intersection between the column and row of interest provides a list of applicable tools and methods. Then, Table 3 can be used to identify the outputs produced by each tool, ensuring that outputs meet project requirements.

Each tool name is hyperlinked to a detailed description to further assist with tool selection. The description includes the purpose of the tool, who developed it, data input requirements, methods for proper use, and where to find the tool. There are trade-offs in terms of effort, data needs, and accuracy. The user should determine which approach best suits their project requirements and resources.

Table 3 summarizes the outputs for each tool and method. Tools and methods are listed in the first column, while outputs are indicated by crosses in the columns. Outputs include current and projected quantities of stored carbon, gross sequestration (i.e., not including carbon lost via decomposition, disturbances, etc.), and net sequestration.

Table 2. Carbon sequestration and storage estimation tools and methods for different asset types

Minimum Data Requirements	Asset Types					
	Local-scale ↔					Landscape-level
	Individual trees	Street and park trees	Urban forest	Wetlands	Forest patches or stands	Land cover patches / landscapes
• Tree species • Diameter at breast height (DBH)	• i-Tree MyTree • i-Tree Design					
• Tree inventory		• i-Tree Eco				
• Plot based data			• i-Tree Eco			
• Area of the restoration project				• Blue Carbon Calculator		
• Forest type • Forest age or volume					• CBM-CFS3 • Volumetric Method	
• Land use land cover						• InVEST Carbon Storage & Sequestration • InVEST Forest Carbon Edge Effect
• Ecological Land Classification (ELC) map						• Business Case for Natural Assets (BC4NA)
• No data						• ABC-Map • i-Tree Canopy

Table 3. Outputs of carbon sequestration by various tools and methods

Tool/ Method	Outputs					
	Current Carbon Stored	Current Gross Sequestration	Current Net Sequestration	Projected Carbon Stored	Projected Gross Sequestration	Projected Net Sequestration
ABC-Map	X			X		
Blue Carbon Calculator			X			X
Business Case for Natural Assets (BC4NA)	X	X		X	X	
CBM-CFS3	X	X	X	X	X	X
InVEST Carbon Storage & Sequestration	X	X				
InVEST Forest Carbon Edge Effect	X	X				
i-Tree Canopy	X	X				
i-Tree Eco	X	X	X	X	X	X
i-Tree Design	X	X		X	X	
i-Tree MyTree	X	X				
Volumetric Method	X	X		X	X	

Details about Carbon Sequestration and Storage Tools and Methods

The following boxes provide details about each of the tools, methods, and resources listed above.

Tool/ Method	ABC-Map: The Adaptation, Biodiversity and Carbon Mapping Tool
Developer	UN FAO, Agence française de développement, Federal Ministry of Food and Agriculture, Germany
Year Developed/ Updated	2021
Asset Types	Continuous land cover across an area of interest
Purpose of Tool/ Method	• The Adaptation, Biodiversity and Carbon Mapping Tool (ABC-Map) is a new geospatial app based on the Google Earth engine. This tool holistically assesses the environmental impact of national policies, plans, and investments in the Agriculture, Forestry and Other Land Use (AFOLU) sectors.
Outputs	• Tonnes of carbon stored per hectare, total carbon, the social cost of carbon at baseline (2015-2019) and in a future period following intervention.
Inputs	• Area of interest (draw on-screen) • First and last year of intervention, intervention area, land use type, and management type
Methodology	• Very little information is provided about the methods and data sources used. • Data at a resolution of 100 m x 100 m is used to produce outputs within the baseline period (2015-2019). Users can also assess the impact of an intervention, but it is not clear what assumptions are built in. • A map showing tonnes of carbon per hectare within the area of interest is produced for the baseline period based on existing data. This section has been developed using the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories 2006, 2014 and 2019 (IPCC, 2006, 2014 and 2019). • Other outputs include graphs of total carbon stocks and the social value of carbon for each year within the baseline period. • The social value of carbon is estimated based on carbon shadow prices obtained from the High Level Commission on Carbon Prices report (Stiglitz et al., 2017). The total carbon stock is converted to t CO_2e (metric tons of Carbon Dioxide equivalents) and then multiplied by the shadow price of carbon, adjusted for its net present value. • After baseline evaluation, users can enter information about their project of interest, including intervention start and end year, project area, land use type, and broad management strategy. • It is possible to use the tool to evaluate the baseline period alone.
When to Use	• To produce results quickly when data is sparse.
Assumptions & Limitations	• Uses existing data at a 100 m resolution • Assumptions and limitations are unknown due to the lack of information regarding methodology.
Areas for Improvement/ Further Research	• More information on the methods and data sources used to create and run the tool. • Finer scale data for areas outside of Europe.
Links & Source	• Online tool: ABC-Map (earthengine.app)

Tool/ Method	Blue Carbon Calculator
Developer	Division of Ecological Restoration and Executive Office of Energy and Environmental Affairs, Commonwealth of Massachusetts
Year Developed/ Updated	2016
Asset Types	Restored wetlands
Purpose of Tool/ Method	• To assess the greenhouse gas impacts of aquatic ecological restoration projects (i.e. how emissions change as a result of a project).

Outputs	• Annual net emissions resulting from changes in wetland land cover for up to 50 years after a restoration project.
	• Results reported as:
	  ○ Tonnes CO_2-C: mass of carbon resulting from CO_2 only
	  ○ Tonnes CH_4-C: mass of carbon resulting from CH_4 only
	  ○ Tonnes CO_2e: mass of CO_2 equivalents resulting from CO_2 and CH_4 combined
	  ○ Gallons of gasoline: Equivalent of CO_2 emissions from consumption of gas (CO_2 and CH_4 combined)

Inputs	• Land area for each type of wetland-related change (see below) from a project.
Methodology	• The tool relies on a look-up table that provides soil emissions (via soil carbon stock, dissolved organic carbon, CO_2, and CH_4) for each type of wetland change defined by IPCC. • Changes include the destruction and creation of wetlands and alterations from one class of saturated land to another. Emissions from gasoline used for restoration projects are also included. • For wetland destruction, the tool considers whether wetland soil is removed and whether wetlands are drained or converted to uplands. • For wetland creation, the tool considers whether drained lands are re-saturated. • The look-up table provides emission factors for each type of change in the wetland (positive or negative) for soil carbon stock (t C/ha), dissolved organic carbon (DOC) (t C/ha/yr), carbon dioxide (t C/ha/yr), and methane (t Ce/ha/year). • Values are sourced from the IPCC's 2013 Wetlands Supplement and are based on IPCC's temperate or cold temperate wet climate types (IPCC 2001). However, emission factors for forested wetlands are based on an analysis of GHG fluxes conducted by the team to develop the tool. • Organic and mineral wetlands are distinguished in the tool; it is possible to specify up to 65 different types of wetlands. • CO_2 and CH_4 emission factors for rewetting of inland wetlands vary with nutrient status and have been built into the calculator.
When to Use	• To assess the impacts of existing or proposed wetland restoration projects on the total carbon emissions budget for several years after completion • Carbon accounting projects
Assumptions & Limitations	• There is a data gap in CO_2 emissions from rewetted inland mineral soils; the IPCC does not report any values for these soils.
Areas for Improvement/ Further Research	• Accounting for GHG emissions associated with the extraction of inland/freshwater organic wetlands requires further investigation
Links & Sources	• Tool and Resources: Blue Carbon Calculator | Mass.gov

Tool/ Method	Business Case for Natural Assets (BC4NA) - Carbon Sequestration Methodology
Developer	Credit Valley Conservation (CVC), in partnership with Green Analytics
Year Developed/ Updated	2020
Asset Types	Ecological Land Classification (ELC) land cover types including Forests, Wetlands, Grasslands, Open Space, and Agriculture
Purpose of Tool/ Method	• To estimate the value of annual carbon sequestration by mature land cover types up to 20 years into the future under the "do nothing," "maintain," and "enhance" scenarios
Outputs	• Tonnes of carbon sequestered per ELC land cover type and monetary value, annually over 20 years
Inputs	• Areas of natural assets, defined as ELC land cover types, in hectares
Methodology	• Area of ELC land cover types (in hectares) is multiplied by an annual, per hectare carbon sequestration rate specific to that land cover type, as informed by scientific literature. • The Social Cost of Carbon ($/tonne), obtained from ECCC (2016)[16], is used to assign a monetary value to carbon sequestration services of natural assets at present value. • Carbon sequestration and its monetary value are quantified in a "do nothing" scenario without the maintenance of assets against damage and risks, a "maintain" scenario, where assets are maintained, and cost of maintenance is incorporated, and an "enhance" scenario, where the sequestration potential of the additional land cover area with restoration potential is considered and valued.
When to Use	• Estimating the sequestration and associated monetary value of mature land cover
Assumptions & Limitations	• Assumes that all of the natural assets assessed are mature and have static carbon sequestration rates
Areas for Improvement/ Further Research	• Improve carbon sequestration rate estimates • Incorporate asset growth/ maturity into valuation projections, i.e., change in sequestration rates over time
Links & Sources	• Credit Valley Conservation Authority (CVC). 2020. Business Case for Natural Assets in the Region of Peel: Benefits to Municipalities and Local Communities. Accessed From: https://cvc.ca/wp-content/uploads/1970/01/BC4NA_in_RoP_f_-20210816_GA_rt120821.pdf. • Social Cost of Carbon: Environment and Climate Change Canada (ECCC). 2016. Technical Update to Environment and Climate Change Canada's Social Cost of Greenhouse Gas Estimates. Accessed from: http://oaresource.library.carleton.ca/wcl/2016/20160502/En14-202-2016-eng.pdf.

[16] From CVC (2020): The social cost of carbon is a monetary measure of the global damage expected from climate change due to the emission of an additional tonne of carbon dioxide in a given year. For the purposes of this study, tonnes of carbon dioxide were converted to tonnes of carbon using equivalent mass. Moreover, a 3% discount rate was applied to these values and they were inflated to 2018 CAD values. See Environment and Climate Change Canada (2016) for more information.

Tool/ Method	Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)
Developer	Canadian Forest Service in partnership with Canadian Model Forest Network
Year Developed/ Updated	2002, continually updated
Asset Types	Forests at the stand and landscape levels, particularly forests managed for timber.
Purpose of Tool/ Method	• A carbon accounting tool to estimate past, present, and future changes in carbon stocks • Simulate forest management scenarios and evaluate their impacts on forest stocks
Outputs	• Carbon stocks and carbon stock changes reported as tonnes of carbon (t C) • Ecosystem Indicators and Ecosystem Transfers • Emissions (from disturbances), Disturbed Area, Age Classes, Age Classes by Time Step, Disturbance Transfers, and Unrealized Disturbance
Inputs	• Volume-over-age/growth-and-yield curves for tree species (e.g. Plonski) • Detailed forestry inventory: dominant species, area, age • Disturbances from wildfire and insects (optional) • Harvest schedule: harvest and silviculture types (possible to specify no harvest). • Land use change information (optional): afforestation, reforestration, deforestation, or other
Methodology	• Method is in accordance with IPPC GHG inventory guidelines. • Simulates dynamic annual steps. • Starts with an initial inventory; annual growth increments are based on growth curves. • Carbon is lost through decomposition, disturbances (e.g. harvest, fire, insects), and changes in land use. • Dead organic matter and its impact on biomass is modelled with an understanding of litterfall, woody debris, ad soil carbon dynamic processes and effects of disturbances. • Includes harvest schedules to estimate volume removed and post-harvest dynamics. • The user inputs values for afforestation, reforestration, and/or deforestation which is used to model increases or decreases in carbon stocks. • It is possible to segment the forest into different species compositions and management regimes. • The model incorporates carbon emitted from management and disturbance as carbon dioxide, methane, and carbon monoxide into calculations of net sequestration. For harvested forests, carbon is stored in timber products. • Spatial and non-spatial models are available.
When to Use	• Simulating the dynamics of all forest carbon stocks if required for the UN Convention on Climate Change. • When more precise estimates of carbon storage and net sequestration are needed. • For forecasting, including understanding the impacts of harvesting. • Reporting on the carbon storage and sequestration contributions of forests to comply with sustainable forest management guidelines and forest certification. • When time, data, and expertise to set up a complex model are available.
Assumptions & Limitations	• Stands are assumed to have a single age. • Forested peatland carbon dynamics are not included. • Does not directly address the impacts of climate change on decomposition rates and forest growth or disturbance regimes.
Areas of Improvement/ Further Research	• More locally applicable growth-and-yield models, leaf litter, woody debris, and soil carbon pool parameters. • Impacts of climate change on forest growth, disturbances, and decomposition.

Links & Sources	• Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.2: user's guide. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. • Manual: https://d1ied5g1xfgpx8.cloudfront.net/pdfs/39768.pdf

Tool/Method	InVEST Carbon Storage & Sequestration Model
Developer	Stanford Natural Capital Project
Year Developed/ Updated	Updated every three months
Applicable Asset Types	Land cover across a landscape
Purpose of Tool/ Method	• To map and calculate the carbon stored within different land uses and cover types. • To map changes in carbon stored between two time periods if land use and land cover maps for each period are available. • Net sequestration for the entire study area is computed (gains subtract losses). • Can estimate the monetary value of carbon storage and sequestration.
Outputs	• Total tonnes of carbon stored • Net carbon sequestered (tonnes of carbon per year) • Raster map showing tonnes of carbon stored per pixel • Raster map showing net sequestration per pixel
Inputs	• Raster of land use land cover (LULC) types (for a specific period) • Optional: A second raster of land use land cover types at another period • Biophysical table that includes a row for each land use land cover type • In a biophysical table, carbon density (t C/ha) values for the following pools for each LULC type: aboveground and belowground living biomass, soil, and dead matter • Optional: Economic data (i.e., price/metric tonne of carbon, market discount in the price of carbon, the annual rate of change for the cost of carbon)
Methodology	• A carbon stock map is calculated by multiplying the area of each pixel with the applicable carbon storage rate (per hectare) within the biophysical table. It also calculates the total carbon stored by summing the calculated carbon stock values of all pixels. • Assumes that carbon sequestration or loss occurs when a change in land cover type increases or decreases the amount of carbon stored. • By inputting two land cover maps from two different periods, the tool estimates carbon sequestration by calculating carbon stored for each map and evaluating the difference between the two time periods. • Net sequestration is the sum of pixel values (net carbon sequestration) calculated in the previous step. • Alternatively, carbon sequestration could be calculated by updating the biophysical parameter table to reflect average carbon sequestration rates (t C/ha/year). Note: this is not the approach intended by the tool developers. • Optional: The market value of net carbon sequestered can be calculated if the user enters the social cost of carbon (per tonne). The tool can also apply discount rates – in Canada, a 10% discount rate is recommended.
When to Use	• This tool is best used to map and calculate the carbon stored and sequestered across a large area such as a landscape (e.g. watershed or municipality). • For demonstrating gains or losses in carbon stored due to changes in land use or land cover type.
Assumptions & Limitations	• Oversimplified carbon cycle - assumes a linear change in sequestration over time. • Assumes a constant carbon storage and sequestration rate per land use type. • Carbon sequestration or loss only identified by changes in land use or land cover type. • Carbon sequestration due to forest growth will not be calculated unless there is a change in land cover type (e.g. from successional forest to mature forest, which is represented in the land cover map).

	• The accuracy of the results depends on the accuracy and spatial resolution of the land use land cover map.
Areas for Improvement/ Further Research	• Carbon storage and sequestration rates for land use land cover types
Links & Sources	• InVest: https://naturalcapitalproject.stanford.edu/software/invest • Guide: http://releases.naturalcapitalproject.org/invest-userguide/latest/carbon_edge.html • Guide Citation: Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D., Fisher, D., Glowinski, K., Griffin, R., Guannel, G., Guerry, A., Johnson, J., Hamel, P., Kennedy, C., Kim, C. K., Lacayo, M., Lonsdorf, E., Mandle, L., Rogers, L., Silver, J., Toft, J., Verutes, G., Vogl, A. L., Wood, S., & Wyatt, K. (2020). InVEST 3.9.0. User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Tool/Method	InVEST Forest Carbon Edge Effect Model
Developer	Stanford Natural Capital Project
Year Developed	Unknown; Regularly updated
Asset Types	Forest and other land cover and land use types
Purpose of Tool/Method	• To map and calculate the carbon stored within different land cover types. It also considers carbon stock degradation, which occurs at forest edges. • Although it is designed for carbon storage estimation, it could also be used to map and calculate carbon sequestration if the biophysical table includes average annual carbon sequestration rates per land use land cover type.
Outputs	• Total tonnes of carbon stored • Raster map showing tonnes of carbon stored per pixel
Inputs	• Raster of land use and cover that includes a forest class. • Biophysical table that includes a row for each land use land cover type. • Carbon density value (t C/ha) for the following pools for each land use and cover type: aboveground and belowground living biomass, soil, and dead matter.
Methodology	• The Forest Carbon Edge Effect Model calculates and maps carbon stored from an input land cover map and a biophysical parameter table which indicates the average tonnes of carbon stored per hectare for each land cover type. Carbon stores can be specified for aboveground biomass, belowground biomass, soil, and dead matter (twigs, leaves, deadwood) as tonnes of carbon per hectare. • It also models carbon stock degradation at forest edges using a distance decay function based on known relationships between distance to the forest edge and carbon storage. Only the above-ground carbon storage estimates are modified based on this function. The model's outputs are a map indicating carbon storage per pixel and an aggregate carbon stored value for the area of interest (AOI) or subunits within the AOI. • The Forest Carbon Edge Effects model could also be utilized to calculate carbon sequestration by updating the parameter table to reflect average carbon sequestration rates (t C/ha/year) per land cover or forest type. Per hectare storage and sequestration rates from this guide and toolbox can be used as inputs (Note: This is not the approach intended by the tool developers).
When to Use	• To map and calculate the carbon stored across a large area such as a landscape, watershed, or municipal jurisdiction • In landscapes with highly fragmented forest patches
Assumptions & Limitations	• The accuracy and reliability of the model rest on the accuracy of carbon storage rates for each land cover or forest type. • The accuracy and precision of the model also depend on the accuracy and spatial resolution of the land use land cover map. • The forest degradation equation is based on empirical studies of carbon degradation in tropical forests, which may be less relevant to temperate forests.
Areas for Improvement/ Further Research	• Carbon storage and sequestration rates for land use land cover types • Localized studies about how carbon storage and sequestration rates decrease with decreasing distance to the forest edge • Include the impacts of edge effects on belowground carbon storage
Links & Sources	• InVEST: https://naturalcapitalproject.stanford.edu/software/invest • Guide: http://releases.naturalcapitalproject.org/invest-userguide/latest/carbon_edge.html • Guide Citation: Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D., Fisher, D., Glowinski, K., Griffin, R., Guannel, G., Guerry, A., Johnson, J., Hamel, P., Kennedy, C., Kim, C. K., Lacayo, M., Lonsdorf, E., Mandle, L., Rogers,

	L., Silver, J., Toft, J., Verutes, G., Vogl, A. L., Wood, S., & Wyatt, K. (2020). InVEST 3.9.0. User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Tool/ Method	i-Tree Canopy
Developer	USDA Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, and SUNY College of Environmental Science and Forestry
Year Developed	2006. Regularly updated. Currently, on v.7.1
Asset Types	Land cover types, including tree canopy
Purpose of Tool/Method	• To calculate the percent and area of land cover classes within the study area, carbon storage, gross carbon sequestration, and other ecosystem services.
Outputs	• Percentage and area of canopy cover and other land cover classes • Total carbon stored and sequestered (gross) as tonnes of carbon (t C) and tonnes of CO_2 equivalents (t CO_2e) • Avoided runoff and air pollution removed
Inputs	• A list of land cover classes of interest • All the other data is collected within i-Tree Canopy
Method	• i-Tree Canopy is a free online tool that uses Google Earth imagery. The user uploads or delineates a study area boundary • i-Tree Canopy then randomly generates point locations within the boundary which a technician classifies by land cover type • The user classifies each point as a land cover type based on the underlying imagery. The greater the number of points classified, the better the accuracy • The proportion of tree cover class within the study area is used to calculate carbon storage and sequestration as well as an economic value • Default "average" kg C/m^2 values are used for the most similar area in the United States, or the user can enter their own values • Because it uses a sample-based method, confidence intervals can be assigned to the calculation of canopy cover percentage
When to Use	• When land cover or canopy cover data is lacking • To quickly calculate and value carbon storage and sequestration provided by trees • To calculate other ecosystem services (avoided runoff and air pollution removal) simultaneously
Assumptions & Limitations	• Uses average values to calculate carbon storage and sequestration values based on US data. • Depends on the accuracy of the land cover classification, which relies on the quality of the underlying imagery
Areas for Improvement/ Further Research	• Use this method outside of the i-Tree Canopy protocol to assess canopy cover and carbon storage and sequestration using better orthophoto imagery • Locally applicable carbon storage and sequestration rates. • The provision of net sequestration rates.
Links & Sources	• i-Tree Canopy: https://canopy.itreetools.org/ • Nowak, D. J. (2020). Understanding i-Tree: Summary of programs and methods. USDA Forest Service. https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs200.pdf

Tool/Method	i-Tree Eco
Developer	USDA Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, and SUNY College of Environmental Science and Forestry.
Year Developed	2006; Most recently updated in 2021 (v6)
Applicable Asset Types	Urban forest: a collection of trees within a study area, municipality, or watershed.
Purpose of Tool/Method	• To characterize a collection of trees (e.g. street trees) or urban forest in terms of species composition, structure, condition, as well as quantify ecosystem services and values including carbon storage and net sequestration • To identify risks (e.g. pests) and forecast future changes
Outputs	• Tonnes of carbon and CO_2 equivalents (t C and t CO_2e) stored • t C and t CO_2e sequestered (gross and net) • Numerous other measures, including tree composition, structure, health, and other quantified co-benefits.
Inputs	**i-Tree Eco Inventory** • A complete inventory of trees of interest, such as street trees • Minimum requirements: species/genus/family/deciduous or coniferous and DBH • Additional recommended information: tree height, crown dieback, crown light exposure **i-Tree Eco Plot-based Sample** • Minimum requirement: same as above, as well as % of plot measured, % tree canopy cover within the plot • Additional recommended information: actual land use, total tree height, crown dieback, crown light exposure
Method	• Carbon storage is based on the estimated biomass of trees, and annual sequestration is calculated by the difference in carbon stored in two years. Carbon stored in year two is based on the expected annual growth rate in diameter at breast height (dbh). • Species-specific data and growth models are used when available. • Plot-based samples are used to extrapolate to the entire study area based on tree measurements, take in plots, tree population, composition, and structure • Net carbon sequestration is calculated by subtracting an estimation of the carbon lost due to more rapid carbon release (e.g., mulching of tree components and burning) and delayed release (e.g., decomposition) from the gross sequestration. • To estimate carbon release, various assumptions are made about mortality, the probability of recording a dead tree, and decomposition rates.
When to Use	• Ideal to use if a complete inventory of trees (for example, street trees or park trees) is available for assessment • For characterizing carbon storage and sequestration across a municipality or watershed • Landscape-level analysis is based on tree-level data, which increases precision and accuracy of results. • For forecasting the future state of the forest and ecosystem service provision.
Assumptions & Limitations	• Biomass and growth rates are not adjusted for changing climate in forecasting. • The advantages and limitations associated with carbon storage estimates are related to biomass estimates based on species-specific data from the United States. • Net sequestration is based on gross sequestration minus losses due to decomposition. Decomposition estimates are rudimentary and based on various assumptions of mortality and decomposition rates.

Areas for Improvement/ Further Research	• Estimates of storage could be improved with additional biomass equations (see planned future improvements below), specifically biomass equations developed for urban conditions. • Improved research on decomposition rates, method of wood decomposition (e.g. burn, mulch, natural decomposition), and mortality rates for urban trees are needed to enhance net sequestration estimates. • More locally applicable data to inform i-Tree Eco use in Canada.
Links & Sources	• i-Tree Eco: https://www.itreetools.org/i-tree-tools-download • Nowak, D. J. (2020). Understanding i-Tree: Summary of programs and methods. *USDA Forest Service*. https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs200.pdf

Tool/Method	Other i-Tree tools: i-Tree MyTree and i-Tree Design[17]
Developer	USDA Forest Service, Davey Tree Expert Company, The Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, and SUNY College of Environmental Science and Forestry.
Year Developed	2006. Regularly updated.
Applicable Asset Types	Individual trees
Purpose of Tool/ Method	• All tools calculate the ecosystem service benefits provided, including carbon stored and gross carbon sequestered. • Design is also used to forecast tree growth into the future, calculate the total benefits of existing trees to date, and calculate the projected total benefits across a future period.
Outputs	• MyTree: Kilograms of CO_2 equivalents (t CO_2e) sequestered per year for all input trees • Design: Kilograms of t CO_2e sequestered annually in the current and future years; Kilograms of t CO_2e stored in the current year; Total t CO_2e sequestered in future years.
Inputs	• Both tools require location, species, planting status (planted or ingrowth), condition, dbh, sun exposure, and distance to buildings (for energy savings) • Design can also accept polygons delineating building footprints (optional)
Method	• Tools use species-specific models to estimate present tree volume and biomass and how it changes over time. These are used to calculate ecosystem service benefits, such as carbon sequestration and stormwater improvements. • Users must visually place trees on an online map before benefits can be calculated.
When to Use	• To quickly evaluate carbon storage and sequestration by individual trees. • To simultaneously calculate multiple ecosystem services (avoided runoff and air pollution removal). • i-Tree MyTree is the easiest to use. • i-Tree Design can be used to predict future benefits.
Assumptions & Limitations	• Tree growth models reflect conditions and climates of the United States
Areas for Improvement/ Further Research	• The i-Tree tools can be improved by including more shrub, tree species, and growth models relevant to Canada.
Links & Sources	• i-Tree MyTree: https://mytree.itreetools.org/ • i-Tree Design: https://design.itreetools.org/ • Nowak, D.J. (2020). Understanding i-Tree: Summary of programs and methods. *USDA Forest Service*. https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs200.pdf

[17] i-Tree Landscape is another online tool in the i-Tree suite which calculates carbon storage and sequestration as well as other ecosystem service benefits at the landscape level and helps to identify tree planting priority areas. However, because it only uses pre-loaded land cover and demographic data for the United States, it cannot be used for Canadian studies.

Tool/Method	Forest Volumetric Method
Developer	Toronto and Region Conservation Authority adapted from standard practices.
Year Developed	2020/2021
Applicable Asset Types	Forests
Purpose of Tool/ Method	• To calculate the mass of carbon stored within a forest and the gross carbon sequestered as a result of growth. • Can be applied to existing forests or future forests based on their projected age.
Outputs	• Tonnes of carbon and CO_2 equivalents (t C and t CO_2e) stored • t C and t CO_2e sequestered annually or between any two growth years
Inputs	• Forest type and composition • Volume of woody biomass (the volume can be estimated using Plonski Yield tables or Petawawa equations) • Optional: Age of forest (if the volume is not available) • Optional: Future age of forest (to calculate gross sequestration)
Method	• Volume is used to calculate above-ground living biomass. Below-ground biomass can be obtained by multiplying above-ground biomass by 0.28. Biomass can be estimated by multiplying the woody volume of a compartment with the average dry weight density for the dominant species[18] and converted into carbon and carbon dioxide equivalents through multiplication factors. • If forest volume is not available, then woody volume can be estimated based on the age and type of the forest by relating it to the closest forest type within the Plonski Yield Table formulations (Payendeh 1991) or Petawawa equations. • Carbon is also stored in the soil, leaf litter, and deadwood in forests. This is not directly incorporated into this method. However, carbon stored per hectare per pool can be gleaned from relevant literature, multiplied by the area of interest, and added to the total carbon derived from the calculations described. • Annual gross carbon sequestration can be estimated from the change in carbon stored between two given years. By calculating the forest volume using the above method, it is possible to estimate net sequestration. The Plonski Yield Table forest type or Petawawa forest type most applicable to the forest of interest should be selected to estimate the expected increase in forest volume between the two years of analysis.
When to Use	• When detailed information is available on the type of forest or forest species composition as well as the forest age or volume
Assumptions & Limitations	• It considers carbon stored within woody material above- and below-ground. Sequestration is a result of the growth of woody volume. • Accuracy depends on volume estimates from the measurements and equations used to model the expected growth in volume. • The forest is even aged • This method calculates the amount of carbon and carbon dioxide stored in the living biomass of trees and does not include soil, leaf litter, and fallen dead wood unless explicitly included.
Areas for Improvement/	• Develop growth and volume models representative of forest types within our jurisdiction, including mixed-age forests.

[18] Dry weight density per tree species can be looked up in the DRYAD, the Global Wood Density Database.

Further Research	• Measure the relationship between forest type, soil, and dead matter carbon storage and sequestration/loss
Links & Sources	• This method is not currently available as a tool. However, it can be implemented in Excel or in scripting languages such as Python or R. • Bonnor, G.M., and S. Magnussen. (1986). Inventory and Growth Predictions of the Petawawa Forest. Information Report PI-X-66. Canadian Forestry Service. Government of Canada. 41 p. • McPherson, E. G., van Doorn, N.S., Peper, P.J. (2016). Urban tree database and allometric equations. Gen. Tech. Rep. PSW-GTR-235. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 86 p. • Nowak, D. J. (2020). Understanding i-Tree: Summary of programs and methods. USDA Forest Service. https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs200.pdf • Payandeh, B. (1991). Plonski's (metric) yield tables reformulated. The Forestry Chronicle, 67(5), 545-546

Glossary

Carbon accounting: bookkeeping of greenhouse gas sequestration, storage, and emissions, usually for carbon emission mitigation efforts.

Carbon cycle: the flow of carbon atoms between terrestrial, aquatic, and atmospheric reservoirs.

Carbon flux: the amount of carbon exchanged between carbon reservoirs.

Carbon offsetting: reducing emissions or increasing storage/ sequestration, often through monetary investment into environmental projects, to compensate for emissions produced elsewhere.

Carbon sequestration: the process of capturing and storing atmospheric carbon dioxide. Carbon sequestration can be reported as a gross rate (excluding emissions) or net rate (sequestration minus emissions, e.g., from vegetation mortality, decomposition, and decay of organic matter, harvesting, human causes, etc.). Carbon sequestration is often reported as an annual, per area rate, in grams per square meter per year (g $C/m^2/yr$) or tonnes/ megagrams per hectare per year (t C/ha/yr or Mg C/ha/yr).

Carbon storage: carbon retained in stocks (e.g. soil, dead organic matter, and living plant material). By storing carbon, ecosystems help keep CO_2 out of the atmosphere, where it would contribute to climate change. Carbon storage is often reported as a per area rate, in grams per square meter (g C/m^2) or tonnes/ megagrams per hectare (t C/ha or Mg C/ha).

Climate change: a long-term change in regional weather patterns, including rainfall, temperature, and humidity.

Ecological Land Classification (ELC): an integrated approach to surveying and classifying land cover where recurring ecological patterns are identified and categorized across the landscape.

Ecosystem services: benefits to society provided by natural assets including economic, environmental, health, and cultural benefits. Ecosystem services are generally categorized into final services, where there is a direct flow of benefits to humans (e.g., stormwater management), or intermediate services, where there are indirect benefits to humans (e.g., carbon sequestration).

Global warming: a rise in average global temperatures observed since the mid-1800s due to emissions of greenhouse gases from human activity, including the burning of fossil fuels, which have amplified the greenhouse effect.

Greenhouse gas (GHG): gases in the atmosphere that absorb and reflect infrared radiation produced by the earth back to the earth's surface, thereby trapping heat and contributing to the warming of the earth's surface and troposphere (the first layer of the atmosphere). Greenhouse gases include carbon dioxide (CO_2), methane (CH_3), ozone (O_3), nitrous oxides (N_2O), and fluorinated gases.

Natural assets: the stock of natural resources or ecosystems that are relied upon and managed, or could be managed, for the sustainable provision of one or more services to communities, including carbon sequestration and storage. Examples of natural assets include forests, wetlands, grasslands, and manicured open spaces.

Net ecosystem production/ productivity (NEP): the net carbon exchange or flux between terrestrial ecosystems (sequestration minus emissions from respiration, litterfall, biomass turnover, disturbances, and sometimes harvesting and decomposition) and the atmosphere. This measure is typically used to describe function at an ecosystem level.

Net primary production/ productivity (NPP): net biomass production within a year, represented as the net carbon uptake or sequestration by vegetation minus emissions (from respiration, litterfall, biomass turnover, disturbances, and sometimes harvesting). This measure describes the function of vegetation alone.

Net-zero/ net negative: a system that sequesters and stores as much (net zero) or more (net negative) carbon than it emits.

Soil organic carbon (SOC): a measurement of the amount of carbon in organic compounds stored in soils. Often acts as a proxy for organic matter in the soil, which is challenging to quantify. Soil organic carbon is usually reported with a depth of measurement (e.g. 30cm) and may be represented as a per area rate [e.g. grams per square meter (g C/m^2) or tonnes/ megagrams per hectare (t C/ha or Mg C/ha)] or concentration [e.g. grams per cubic meter (g C/m^3) or percent (%) SOC].

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Appendix A: Methods for Literature Review Used to Obtain Carbon Storage and Sequestration Information for Land Cover Types

This appendix outlines the literature review process and selection of carbon sequestration and storage information specific to each land cover type.

Manicured Open Space

The literature was reviewed to obtain carbon storage and sequestration information for Kentucky Bluegrass (*Poa pratensis*), which comprises most manicured open spaces and lawns in Ontario[19]. Carbon sequestration and storage information grouped by lawn age (i.e. establishment to 25 years old and over 25 years old). This distinction was chosen because carbon sequestration significantly decreases after 25 years of establishment as the soils become saturated with carbon (Qian and Follett 2002; Selhorst and Lal. 2013). Within each lawn age group, carbon sequestration rates were averaged from the literature[20] to create a single rate for lawns up to 25 years old and another rate for lawns over 25 years old. The carbon storage rate from Selhorst and Lal (2013) was selected for reference in the database because it was the most recent study on turfgrass and lawns referenced in the literature review.

Forest

The literature was reviewed to obtain carbon sequestration and storage information for forest land cover types, with preference given to studies from Ontario. Research suggests that carbon sequestration and storage rates for forests are highly dependent on environmental conditions, including soil type, pH, climate, historic and current land use, and species composition (Chen et al. 2003, Morris et al. 2007, Nowak 2020). Therefore, it was essential to prioritize local studies or studies with environmental conditions and species similar to those in CVC, TRCA, and LSRCA's jurisdictions.

Carbon sequestration and storage rates also change with forest growth and development (Chen et al. 2003, Nowak 2020), so it was important to account for this in our database. Therefore, carbon sequestration and storage information was grouped by forest age notably, Young, Mature, and Old-Growth Forest, as defined by the Ecological Land Classification Manual (CVC 1998).

The studies reviewed focused on a wide range of forests types and ages, so carbon sequestration and storage rates were not averaged. Instead, representative forests were selected to exemplify rates of a particular forest type and age in the database (e.g. a 34-year-old White Pine plantation, examined in Turkey Point, Ontario, by Peichl et al. 2010, was used to represent rates for a mature conifer plantation in Ontario). Standard error was reported alongside sequestration and storage rates when available in the literature.

A conservative approach was taken to documenting carbon sequestration rates for forests; above-ground net primary production (ANPP) was reported in tonnes of carbon per hectare per year (t C/ha/yr). Carbon sequestration can be measured in net primary production (NPP) and net ecosystem production (NEP).

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[19] See this document by the Ministry of Agriculture, Food and Rural Affairs regarding species that dominate manicured lawns in Ontario: http://www.omafra.gov.on.ca/english/crops/facts/08-025w.htm#turf

[20] Rates selected from the literature were estimated under similar lawn maintenance conditions (e.g. watering once a week, mowing with clippings returned to lawn, etc.).

Where NPP measures the carbon uptake by vegetation, and NEP accounts for the net carbon exchange between terrestrial ecosystems (including soils) and the atmosphere (Chen et al. 2003). Therefore, NPP likely underestimates the total carbon sequestration of a forest ecosystem[21]. However, NPP was the most commonly reported carbon sequestration metric for forests. If another metric was reported, this was noted in the database.

Wetlands

The literature was scanned to obtain Ontario-specific carbon sequestration and storage information for wetlands. This information was used to support the findings of a study on carbon sequestration and storage in wetlands across the Lake Simcoe watershed (Pendea 2019). Due to the local relevance of this research, the rates from this study were used to represent rates of various wetland types. Other literature was used to validate these rates. Net annual carbon sequestration was reported for each wetland type as an average of empirical measurements taken between 2017 and 2019.

Like other land cover types, wetlands naturally release carbon through respiration and decomposition. The destruction of wetlands by humans is particularly concerning because it releases large stocks of carbon dioxide (CO_2) and more potent gases like methane (CH_4) and nitrous oxide (N_2O). Wetlands should be protected since it would take decades for a newly established or restored wetland establishment to become a GHG sink. Protection of wetlands and their carbon stores can be prioritized through reducing:

- Wetland drainage and other land and water management practices that lead to dewatering of wetlands,
- Fires in wetlands (especially in cases of prolonged drought), and
- Peat harvesting and other similar intrusive and destructive practices.

Grasslands

Carbon storage and sequestration information for grasslands were obtained through a literature review. Although the studies found were mainly outside of Ontario, the land cover types in these studies were also common in southern Ontario. A single representative rate for cultural meadow, the common grassland type in southern Ontario, was selected from studies that were closest or most applicable to grasslands in Ontario. Other studies were used to validate the applicability of the rate.

Agricultural Lands

Conclusions from the literature review on carbon sequestration and storage from agricultural land included refraining from providing representative carbon rates for agricultural land cover types at this time. In addition to the high variability in reported carbon rates (see explanation in the main report), challenges were identified in using Ecological Land Classification (ELC) mapping to apply these rates. There is a mismatch between how agricultural land cover types are defined by the ELC and in empirical studies, making connecting rates to land cover types challenging. Accounting for carbon on agricultural land will

[21] NPP is defined as the sum of all biomass production during a year. It should ideally include the sum of all biomass increments minus all losses due to litterfall, biomass turnover, disturbances, and harvesting, however, it is not always clear what is included in studies. NEP is defined as NPP minus all decomposition losses (CBM-CFS3 User Guide, p. 268).

require detailed mapping, including crop type, tillage practice, and rotation, which is information not included with ELC mapping.

Agricultural land cover types as defined by ELC (Intensive and Non-intensive Agriculture) are not related to agricultural practices, which studies suggest influence carbon storage and sequestration. These ELC definitions come from a visual land cover analysis (i.e. interpretation from air photos). The ELC manual generally defines Intensive Agriculture as:

> Cultivated fields producing crops in varying degrees (e.g. corn, soybean, and wheat).

and Non-intensive Agriculture as:

> Fields dominated with herbaceous vegetation and grasses with an understory of similar material in a state of decay, including pasture and grazing areas. Weedy hay and pasture cover more than 50 percent of the area, associated with extensive or unconfined livestock grazing. There should be minimal evidence of recent cultivation.

These land cover definitions cannot be easily connected to carbon storage and sequestration rates. Agricultural practices which are known to influence carbon storage and sequestration, including tillage, crop rotation, and intercropping (Congreves et al. 2014; Ogilvie 2021), are included in both “Intensive” and “Non-intensive” ELC land cover (Eastman and Tarlo, CVC, pers. comm.).

For carbon accounting, land use classification for agriculture should relate to farming practices, highlighting the need for a resource that spatially houses this information. Remote sensing of crop type[22], together with ELC cover type, might be able to inform rough estimates of carbon sequestration from agriculture. Still, additional information is needed for more accurate estimations (e.g. harvested yield, tillage practice, depth and frequency of tillage, cover crops used, fertilizer application, etc.). This data should also be paired with measurements of carbon sequestration and storage from soil sampling to validate estimates of carbon from other models. Ideally, this sampling should be repeated over a long period of time (i.e., over 20 years) to monitor trends in SOC (M. Oelbermann, pers. comm.).

[22] See: https://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9

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Appendix B: Supplementary Carbon Storage and Sequestration information by Land Cover Type

Please see the attached Microsoft Excel document for additional information about carbon storage and sequestration for each land cover type. Detailed information about carbon storage and sequestration from a study site (e.g. carbon sequestration from leaves, root decomposition, above and below ground carbon, etc.), was recorded here, if provided. The table structure follows that of IPCC's recommendations for carbon reportion from land cover types (see Paustian et al. 2006).

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