Credit Valley Conservation
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Toronto and Region Conservation Authority

Lake Simcoe Region conservation authority

Natural Asset Carbon Assessment Guide and Toolbox

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Version 2.0

Prepared by

Credit Valley Conservation Authority,

Lake Simcoe Region Conservation Authority, and

Toronto and Region Conservation Authority

Authors: Owen Royall (Credit Valley Conservation: CVC)
Lauren Moretto (Credit Valley Conservation: CVC)
Tracy Timmins (Toronto and Region Conservation Authority: TRCA)
Fabio Tonto (Lake Simcoe Region Conservation Authority: LSRCA)
Contributors: Noah Gaetz (TRCA)
Angelo Filicetti (TRCA)
Tatiana Koveshnikova (CVC)
Bill Thompson (LSRCA)
Sarah Kirilenko (LSRCA)
Kaitlyn Read (LSRCA)

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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.
Version 2.0 includes updated rates and values from literature reviews, data analysis, and fieldwork, and includes an improved method for synthesizing and evaluating evidence (Appendix A).

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, Lake Simcoe Region, and surrounding areas. 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 rates and storage values 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 (sequestration) and storage of carbon from the atmosphere. The carbon can be stored in living biomass, leaf litter, deadwood such as downed trees or branches, 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 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 carbon 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 and **climate change**.

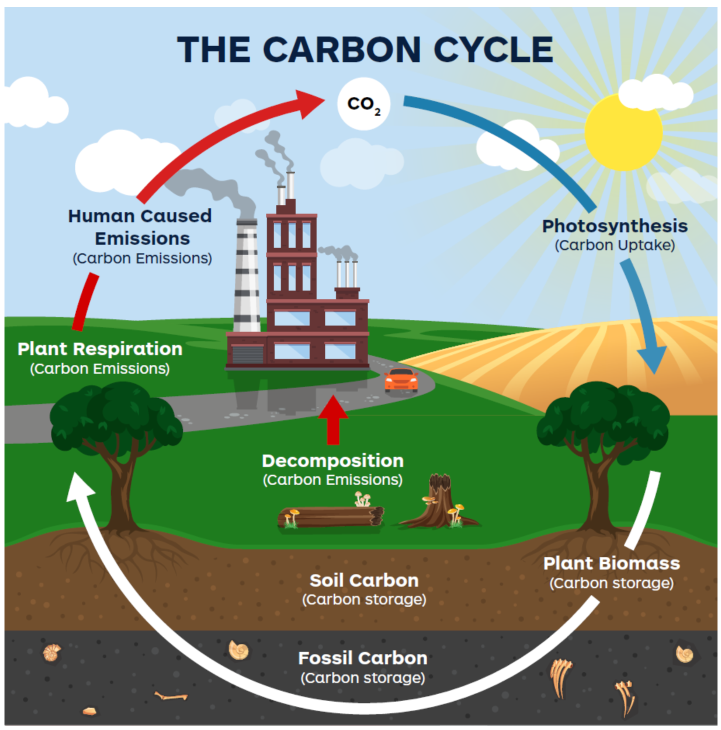

Figure 1. A simplified representation of part of the carbon cycle. Note that aquatic systems and other living organisms also contribute to carbon exchange but are not included in this image. Image credit: CVC.

[1] See Chapter 7.3: The Carbon Cycle and the Climate System by the IPCC for more background information about the carbon cycle.

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 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).

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[2] See projections of CO_2 concentrations from the IPCC

[3] See Marshes Dominated by Phragmites australis (European Reed) below as an example

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 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

[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." 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).

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 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 rates and storage values 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 carbon sequestration rates and storage values for local land cover types, including forests, wetlands, grasslands, manicured open spaces, and aquatic habitats. 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.

Appendix A and B contain supplementary information about carbon storage and sequestration for different land cover types. Appendix A summarizes the methodology used to apply confidence labels to different sources of carbon storage and sequestration. Appendix B provides additional carbon storage and sequestration values not included in the main database and a breakdown of carbon pools measured in each source.

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. Additional tools and techniques will be added in future versions. This is version 2.0. Updated from version 1.4, this version has updated carbon sequestration rates and storage values (presented in Section 2) from a more recent literature review (CVC, 2024a), analysis of datasets (CVC, 2024b), and fieldwork (LSRCA, 2025). Also, this version has an updated method for synthesizing and evaluating evidence (Appendix A) to determine which sources should be included in the database.

[9] The "Greenhouse Gas Equivalencies Calculator", provided by Natural Resources Canada, converts tonnes of carbon to relatable statistics.

Section 2: Carbon Sequestration Rates and Storage Values 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 and values based on empirical studies from the scientific literature or gray literature sources. To compile a carbon sequestration and storage database, we conducted multiple rounds of literature reviews (once in 2020, once in 2023 (see CVC, 2024a)), performed an analysis of some local data sources (CVC, 2024b), and conducted field work on two ecosystem types (LSRCA, 2025). Carbon sequestration rates are presented for the following land cover types: manicured open space, grassland, forest, wetland, and aquatic land cover types. Carbon storage values are presented for forests only. This is due to a) lack of data for manicured open space, grassland and aquatics, and b) the fact that in wetlands, most carbon is stored in sediment, and sampling the full depth of wetland sediment can be extremely difficult and is rarely done in studies.

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

Agricultural Lands

We omitted agricultural land cover types from the database due to the high variability in carbon sequestration and storage rates reported. It is challenging to identify clear trends in carbon sequestration and storage from agricultural land cover types 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[10]. 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

[10] 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."

term. These sustainable practices also benefit crop yields, stability, and resilience to adverse environmental conditions and climate change[11]. These practices include:

- Rotating crops (e.g., with alfalfa, winter wheat, or red clover),
- 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[12],
- 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[13]), 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[14].

Forest

The sequestration and storage of carbon in forests are complex, and therefore, studies often note a variety of additional measurements. These measurements are 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.

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)

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[11] 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, Farmers for Climate Solutions, Ontario Soil Network, and the Canadian Forage and Grassland Association are also working with farmers to promote sustainable farming practices.

[12] 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.

[13] Rathgeber 2021: Forage Best Management Practices for Enhancing Soil Organic Carbon Sequestration

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

and more potent gases like methane (CH_4) and nitrous oxide (N_2O) are released. Wetlands should be 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).

Combining Multiple Carbon Values

After several literature reviews and the analyses of various datasets, we had many carbon stock and sequestration values we could report. In many cases, this left us with multiple values for the same land cover type. For the ease of the reader, we wanted to have one value associated with each land cover type. This Involved combining similar values.

For most land cover types, the two main carbon pools measured in studies were sediment carbon and plant biomass. For wetlands, since there were more studies that looked at sediment carbon, we had enough studies of 'high' confidence (see Confidence Labels below, and Appendix A) to average multiple rates of sediment carbon sequestration of the same land cover type of only 'high' confidence. Due to the fewer studies on plant biomass rates, we averaged studies of medium and high confidence. We then added sediment and biomass carbon sequestration rates of the same land cover type to produce one complete rate. For example, if coniferous swamps had studies V, W, and X (all high-confidence studies) report sediment carbon sequestration rates, and studies Y and Z report plant biomass carbon sequestration rates, we would average the reported values of V, W and X, then average Y and Z, and add the two averages together for one complete carbon sequestration rate of both carbon pools. The un-averaged values can be found in Appendix B.

For forest land cover types, we employed a similar tactic of combining like biomass and sediment values (when present) that was used for wetland studies. However, in addition, we grouped carbon storage values and sequestration rates of similar age group, since carbon sequestration rates differ at different forest ages (e.g. Chen et al. 2003, Nowak 2020). We used age groups from Lee et al. (1998) (Table 1) to combine similar values. Since the addition of age groups for each land cover type increased the total number of possible single values, we considered values of both medium and high confidence to combine into one value. For some forest land cover types, we had to combine the categories of mid-aged and mature due to either data availability issues, or due to study plots/sites in the same dataset covering both mid-aged and mature age classes, meaning we were unable to separate the two age classes. The un-averaged values can be found in Appendix B.

Table 1: Age groups used to combine similar forest carbon storage and sequestration values (from Lee et al., 1998).

Code	Definition
Pioneer	A community that has invaded disturbed or newly created sites and represents the early stages of either primary or secondary succession
Young	A community that has not yet undergone a series of natural thinnings and replacements; plants are essentially growing as independent individuals rather than a phytosociological community
Mid-aged	A community that has undergone natural thinning and replacement as a result of species interaction and often contains examples of both early and late successional species
Mature	A successionally maturing community dominated primarily by species that are replacing themselves and are likely to remain an important component of the community if it is not disturbed again; significant remmants of early seral stages may still be present
Old Growth	A self-perpetuating community composed primarily of late seral species that show uneven stand age distribution, including large old trees (generally older than 120 years) without open-grown characteristics

Confidence Labels

There were many sources identified as having carbon sequestration rates and storage values that we could include in the database. However, not all sources were of the same quality. To account for differences in quality, we have developed a standardized way to compare and evaluate the evidence and report values that have the greatest validity and reliability (see Appendix A for more details). This approach is based on methods from *Transforming Conservation: A Practical Guide to Evidence and Decision Making* (Sutherland, 2022), where three criteria are considered: i) information reliability, ii) relevance, and iii) source reliability.

Information reliability relates to the study methods. This includes considering the number of plots/sites in the study, number of years the plots were visited, how detailed and robust the measurements taken were, and how many carbon pools were measured in the study. Relevance evaluates how relevant the findings are to local ecosystems. In this case, relevance is determined by how similar the study site(s) is/are to the **Ecological Land Classification** (ELC) (see Appendix C for ELC codes and definitions used in this report) community types found in CVC, TRCA, and LSRCA's jurisdictions. Source reliability considers who the information comes from and whether they are to be trusted in terms of their expertise. We prioritize peer-reviewed articles from prestigious journals and studies over grey literature. Based on pre-determined definitions for each value, evidence is ranked by each criterion on a scale from zero to four (Appendix A).

By combining the three scores for information reliability, relevance, and source reliability, we calculate an overall confidence score, which we convert to categorical confidence label. We use this confidence label to inform which carbon storage/sequestration values will be put in the main database (Tables 2 and 3) versus Appendix B (an accompanying spreadsheet). More details on how confidence labels were calculated can be found in Appendix A. The confidence label for each source in the database can be found in Appendix B.

The Database

The database (Tables 2 and 3) includes a description of the land cover type, an average net carbon sequestration rate (Table 2) or carbon storage value (Table 3), and information about sources, and location(s) of data collection. The first four columns of the tables describe the land cover type(s) in various ways (including use of ELC codes; see Appendix C for ELC definitions) to help identify land cover types suitable for the application of carbon sequestration and storage rates. Note that the sequestration table (Table 2) 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 ecosystems 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 database includes total net carbon sequestration rate (Table 2) and storage values (Table 3) for each land cover type, as well as a breakdown of biomass and sediment carbon sequestration rates and storage values. Biomass (including above ground and below ground, unless otherwise mentioned) and sediment represent the two main carbon pools measured in studies. This breakdown in the database is provided so the user can have more context of where carbon is being sequestered and stored in these ecosystems. Note that in wetlands studies, sediment carbon sequestration represents a very long-term accumulation of carbon (sediment cores are often dated >50 years), whereas wetland biomass carbon sequestration represents a much shorter-term (most studies looking at wetland biomass are 1-3 years).

The information in the database can be used to estimate carbon storage and sequestration across a landscape based on studies done on similar ecosystem types. 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.

Database for Land Cover-Based Carbon Sequestration Rates and Storage Values

Table 2: Carbon sequestration rates by ELC land cover type

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)	Biomass Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Sediment Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Reference(s)	Location(s) of Study/ Measurements
Open space	Manicured lawn	MOS, MOI, MOC, MOO, MOP, MOR	<25 years old	**1.5**		1.5 (1.0-1.32)	Qian and Follett, 2002, Selhorst and Lal, 2013, Zirkle et al., 2011	Wooster, Ohio, USA; USA-wide; Delaware, Ohio
Open space	Manicured lawn	MOS, MOI, MOC, MOO, MOP, MOR	>25 years old	**-0.03**		-0.03 (-0.34-0.62)	Qian and Follett, 2002, Selhorst and Lal, 2013, Zirkle et al., 2011	Wooster, Ohio, USA; USA-wide; Delaware, Ohio
Grassland	Cultural meadow	CUM		**1.07**		1.07 (0.12-3.9)	Anderson et al., 2008	Minnesota
Forest	Cultural Hedgerow	CUH	Adjacent to agricultural fields	**2.0**	1.7	0.3	Drexler et al., 2021	Temperate climates (meta-analysis)
Forest	Coniferous forest	FOC	Mid-Aged/Mature	**3.4**	3.4 (2.0-6.0)		CVC, 2024b, Ofosu et al., 2022	Oxford and Huron counties, CVC jurisdiction
Forest	Deciduous forest	FOD	Mid-Aged	**6.9**	6.9		Ofosu et al., 2022	Oxford and Huron counties
Forest	Deciduous forest	FOD	Mature	**2.4**	2.4 (2.0-2.8)		Beamesderfer, 2019, Beamesderfer et	Pellston (Michigan), and Walsingham in Norfolk County

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)	Biomass Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Sediment Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Reference(s)	Location(s) of Study/ Measurements
							al., 2020, Gough et al., 2013,	
Forest	Deciduous forest	FOD	Old growth	**2.4**	2.4		CVC, 2024b	CVC jurisdiction
Forest	Mixed forest	FOM	Mid-Aged/Mature	**1.9**	1.9 (1.53-2.3)		CVC 2024b, Gough et al. 2008	Pellston (Michigan), and CVC jurisdiction
Forest	Deciduous plantation	CUP1	Pioneer	**1.7***	1.7		Bazrgar et al. 2022	Kemptville
Forest	Deciduous plantation	CUP1	Young	**1.09***	1.09 (0.91-1.4)		Bazrgar et al. 2022	Claremont and Guelph
Forest	Deciduous plantation	CUP1	Mid-Aged/Mature	**3.36**	3.01 (2.01-4.0)	0.35	CVC 2024b, Morris et al. 2007	Cass County (Michigan)
Forest	Coniferous plantation	CUP3	Pioneer	**0.87**	0.87 (0.71-1.03)		Chan et al. 2018, Peichl et al. 2010	Walsingham in Norfolk County
Forest	Coniferous plantation	CUP3	Young	**3.1**	2.8 (0.23-5.88)		Arain et al. 2022, LSRCA, 2025, Peichl et al. 2010	Walsingham in Norfolk County, CVC, LSRAC, TRCA jurisdictions
Forest	Coniferous plantation	CUP3	Mid-aged	**3.73**	3.47 (2.25-5.38)	0.26	Arain et al. 2022, Morris et al. 2007, Peichl et al. 2010	Cass County (Michigan), Walsingham in Norfolk County

* Above ground net primary productivity only

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)	Biomass Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Sediment Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Reference(s)	Location(s) of Study/ Measurements
Forest	Coniferous plantation	CUP3	Mature	**1.8**	1.8 (1.27-2.18)		Arain et al. 2022, Beamesderfer 2019, Peichl et al. 2010	Walsingham in Norfolk County
Wetland	Bog	BOT	Treed bog	**5.11**	1.46	3.65	Pendea, 2019	Lake Simcoe Watershed
Wetland	Fen	FES	Shrubbed fen	**3.48**	2.77	0.71	Pendea, 2019	Lake Simcoe Watershed
Wetland	Marsh	MAM	Meadow marsh	**5.3**	3.69 (0.25-12.05)	1.6 (1.05-2.35)	Loder et al. 2023, LSRCA, 2025, Pendea, 2019, Pendea et al. 2023	Long point, ON, and CVC, TRCA, LSRCA jurisdictions
Wetland	Marsh	MAS	Shallow marsh	**9.4**	8.55	0.81 (0.62-1.1)	Creed et al. 2022, Pendea, 2019, Pendea et al. 2023	Onondaga, ON, and CVC, TRCA, LSRCA jurisdictions
Wetland	Swamp	SWC	Coniferous swamp	**3.42**	2.94**	0.49 (0.18-0.76)	Dazé et al., 2022, Ott and Chimner, 2016, Pendea et al. 2023	Chepstow, ON, Michigan and Minnesota, and Lake Simcoe Watershed
Wetland	Swamp	SWD	Deciduous swamp	**3.49**	2.94**	0.55 (0.31-0.79)	Dazé et al., 2022, Pendea et al. 2023	Chepstow, ON, and Lake Simcoe Watershed
Wetland	Swamp	SWM	Mixed swamp	**3.81**	2.94	0.87	Pendea, 2019	Lake Simcoe Watershed

** Rate used from mixed swamp (SWM) community type

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)	Biomass Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Sediment Carbon Sequestration Rate (t C/ha/yr) (min-max values, if applicable)	Reference(s)	Location(s) of Study/ Measurements
Wetland	Swamp	SWT	Thicket swamp	**3.6**	1.99	1.6 (1.5-1.7)	Pendea, 2019, Pendea et al. 2023	Lake Simcoe Watershed
Aquatic	Shallow aquatic	SAF	Floating leaved shallow aquatic	**3.33**	2.38	0.95	Pendea, 2019	Lake Simcoe Watershed
Aquatic	Open aquatic	OA	Open aquatic	**0.87**		0.87	Blodau et al., 2018	Cook's Bay, Lake Simcoe

Table 3: Carbon storage values for forested ELC land cover types.

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Carbon stock value (t C/ha)	Biomass carbon stock value (t C/ha) (min-max values, if applicable)	Sediment carbon stock value (t C/ha) (min-max values, if applicable)	Reference(s)	Location(s) of Study/ Measurements
Forest	Coniferous forest	FOC	Mid-Aged/Mature	**487.5**	215.7 (191.8-239.6)	271.8	CVC 2024b, Ofosu et al. 2022	Oxford and Huron counties, CVC jurisdiction
Forest	Coniferous forest	FOC	Old growth	**930.8**	272.5	658.3	Ofosu et al. 2022	Oxford and Huron counties

Land Cover/ Natural Asset Type	Land Cover Community Type/ Ecosystem	Relevant ELC Community Code(s)	Land Cover Details/ Notes	Carbon stock value (t C/ha)	Biomass carbon stock value (t C/ha) (min-max values, if applicable)	Sediment carbon stock value (t C/ha) (min-max values, if applicable)	Reference(s)	Location(s) of Study/ Measurements
Forest	Deciduous forest	FOD	Mid-Aged/Mature	**584.6**	227.7 (140.5-314.9)	356.9	CVC 2024b, Ofosu et al. 2022	Oxford and Huron counties, CVC jurisdiction
Forest	Deciduous forest	FOD	Old growth	**568.3**	242.7 (167.0-358.3)	325.6 (72.9-578.3)	CVC 2024b, Morris et al. 2007, Ofosu et al. 2022	Oxford and Huron counties, Cass County (Michigan), CVC jurisdiction
Forest	Mixed forest	FOM	Mid-Aged/Mature	**173.7**	173.7 (166.5-180.8)		CVC, 2024b	CVC jurisdiction
Forest	Deciduous plantation	CUP1	Mid-Aged/Mature	**194**	111 (94.9-127.6)	82.4 (70.2-93.2)	CVC, 2024b, Ijzerman et al. 2022, Morris et al. 2007	Guelph, ON, Cass County (Michigan), CVC jurisdiction
Forest	Coniferous plantation	CUP3	Pioneer	**25.9**	25.9 (9.2-42.6)		Kula 2013, Peichl et al. 2010,	Walsingham in Norfolk County
Forest	Coniferous plantation	CUP3	Young	**50**	50 (39.3-61)		Peichl et al. 2010	Walsingham in Norfolk County
Forest	Coniferous plantation	CUP3	Mid-aged	**171.6**	100 (75.2-136)	71.6 (64.6-78.1)	Ijzerman et al. 2022, Kula 2013, Morris et al. 2007, Peichl et al. 2010	Guelph, Walsingham in Norfolk County, Cass County (Michigan)
Forest	Coniferous plantation	CUP3	Mature	**144.3**	144.3 (128.5-160)		Kula 2013, Peichl et al. 2010	Walsingham in Norfolk County

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 4 and 5 provide guidance on selecting the most appropriate tools and methods for various tasks. Table 4 indicates which tools are suitable based on the asset type and data requirements, while Table 5 summarizes the outputs provided by each tool.

Deciding on a Tool or Method

In Table 4, 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 5 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 5 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 4. Carbon sequestration and storage estimation tools and their minimum data requirements for different natural asset types. Natural asset types are sorted left to right by smaller-scale natural assets to larger-scale.

Minimum Data Requirements	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 5. Outputs of carbon sequestration by various tools and methods

Tool/Method	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)[15], 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. • 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.

[15] 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. • User manual

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 tool • InVest Guide • 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 tool • InVest Guide • 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 • Nowak, D. J. (2020). Understanding i-Tree: Summary of programs and methods. USDA Forest Service.

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 • Nowak, D. J. (2020). Understanding i-Tree: Summary of programs and methods. *USDA Forest Service*.

Tool/Method	Other i-Tree tools: i-Tree MyTree and i-Tree Design[16]
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 • i-Tree Design • Nowak, D. J. (2020). Understanding i-Tree: Summary of programs and methods. *USDA Forest Service*.

[16] 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[17] 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.

[17] 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: Method for Synthesizing and Evaluating Evidence

Multiple rounds of literature review, database analysis, and fieldwork produced many carbon sequestration rates and storage values from various sources that we could include in the database of this report. However, the values differed in quality of methods, source, relevance. To showcase the best values, it is necessary to evaluate and synthesize these study findings to provide a recommended value for local community types[18]. Recommended values could be selected from the best studies or be an average of several good studies. To select or calculate an appropriate value, the studies need to be evaluated for their quality, reliability, and relevance. Thus, we developed a method of comparing and evaluating evidence to produce a confidence label for each value, which is described in this section. Methods for establishing confidence labels are currently limited to forests and wetlands, as these two land cover types have many sources needing combining and vetting.

A1. How to Establish a Confidence Label

The approach for creating a confidence label is based on the book *Transforming Conservation: A Practice Guide to Evidence and Decision Making* by William Sutherland (2022). Sutherland outlines three important criteria for determining an overall score: Information reliability, source reliability, and relevance (described in Section 2: *Confidence labels*). Sutherland recommends that each one of these variables be given a score (Table 6). The individual scores can be summed to obtain an overall score.

Table 6: Criteria for classifying evidence weight scores from Sutherland (2022), Table 2.3

Information reliability		**Source reliability**		**Relevance**	
Very reliable approach	5	Considerable trust	5	Extremely relevant	5
Moderately reliable	4	Moderate trust	4	Very relevant	4
Weakly reliable approach	3	Some trust	3	Relevant	3
No knowledge of approach	2	No knowledge of source	2	Somewhat relevant	2
Some concerns over approach	1	Some concerns over reliability	1	Not very relevant	1
Considerable concerns over approach	0	Serious concerns over reliability	0	No relevance	0

Here, we adapt this system. We changed the scores of each criterion to range from zero to four. The sum of each score results in an overall confidence score, and we translate the confidence score into a categorical confidence label of 'high', 'medium', or 'low.'

A1.1 Information Reliability for Wetland Studies

We created separate scoring criteria for wetland information reliability since methods for assessing carbon sequestration in wetlands differed from forests. The general scoring system for information reliability between forests and wetlands remained similar, with the major difference being a separate column for years of the study instead of flux measurements (Table 7), as flux measurements are very rare

[18] Note: All relevant studies and their rates are included in an accompanying Appendix B.

in wetland studies. We wanted a separate column for years of study because soil cores (often taken in wetland studies) can cover a wide range of years, and the difference in accuracy between a 15-year-old core and a 70-year-old core is minimal, so binning year ranges made more sense than multiplying years by sites (as was done with forest studies).

Table 7: Points to be attributed to each information reliability criteria's range for wetland studies

Points	Number of Samples (# independent sites x # of plots/site)	Number of years (soil core age or # years revisited)	Carbon Pools Assessed	Variables Measured
1	> 10	> 10	Very complete picture of carbon pools (e.g. flux towers, or measurements of aboveground biomass, belowground biomass, soil/sediment, detrital (when applicable), and decomposition considered)	Very detailed measurement taken (e.g. core depth, exact steps of processing core, detailed measurements of AB and BG biomasses, decomposition rates explained)
0.75	6 to 10	4 to 10	Most carbon pools measured (missing one of aboveground biomass, belowground biomass, soil/sediment, detrital (when applicable), and decomposition considered	Detailed
0.5	3 to 5	2 to 3	Some pools assessed (only a soil/sediment core, only aboveground and belowground biomass, and decomposition considered)	Some details
0.25	1 to 2	1	Few carbon pools measured (only a soil/sediment core, only aboveground and belowground biomass, and decomposition **not** considered)	Few details
0	0	0	No details	No details

Contrary to forest information reliability scoring, we did not think weighting the scores was necessary. The main reason for weighting the scores of forests was to put greater value to more samples, as there can be great variability within and between forest sites. However, the variability within wetland sites was small, especially studies that used sediment core methods (e.g. Bernal and Mitsch, 2013 and Chu et al., 2015). We will therefore weigh all information reliability criteria equally for wetland studies. Information reliability scores less than or equal to 1 were automatically excluded from further consideration for the main database, but will be available in Appendix B.

A1.2 Information Reliability for Forest Studies

We evaluated information reliability for forest studies as a two-step process. First, there are 4 different criteria to evaluate information reliability (see Table 8), these are:

(i) Biometric plots x sampling years – An approximate value of field sampling intensity in a study. Plots we define as quadrats or transects of any shape/size, note, multiple plots may occur within a single site. We define years as the number of years most metrics were re-measured. For each additional year after the first, 0.25 was added onto this value. Therefore, one year was 1x, two years was 1.25x, three years was 1.5x, etc. This is relevant for both carbon stock and sequestration studies;

(ii) Flux tower site x years – The number of flux towers functioning multiplied by the number of years in operation to get an approximate value of flux tower intensity. This was made a separate criterion as this is a more expensive and accurate way of measuring sequestration than biometric methods, so fewer flux towers could score as high as more sites with biometric sampling. This is only relevant for carbon sequestration studies;

(iii) Carbon pools assessed – How many and how detailed carbon sequestration and stock pools were analyzed; and

(iv) Variables measured - How many and how detailed independent and/or dependent variables were measured

Each of the 4 criteria were attributed points, ranging from 0 to 1, with 0 being the lowest and 1 being the highest, in 0.25 increments.

Table 8: Points to be attributed to each information reliability criteria's range for forest studies

Points	Number of Samples: (#biometric plots x # of sampling years)	Number of Flux Tower Samples (# flux tower sites x # of years)[19]	Description of Carbon Pools Assessed	Number of Variables Measured
1	> 30	> 10	Very detailed (complete description of carbon pools (e.g. size class of trees,	Very detailed measurement taken (e.g. tree height,

[19] This is only applicable to sequestration studies.

Points	Number of Samples: (#biometric plots x # of sampling years)	Number of Flux Tower Samples (# flux tower sites x # of years)[19]	Description of Carbon Pools Assessed	Number of Variables Measured
			shrubs, and deadwood, detritus, organic or inorganic soil carbon)	crown width, dieback, in addition to DBH & species)
0.75	> 20 to 30	> 6 to 10	Detailed	Detailed
0.5	> 10 to 20	> 2 to 6	Some details	Some details
0.25	> 0 to 10	> 0 to 2	Few details (e.g. just notes that "living forest biomass" was assessed)	Few details (only DBH or unclear what was measured)
0	0	0	No details	No details

The second step involved applying weights to each of these 4 criteria to best reflect their overall importance to the information reliability Score (see Table 9), this was repeated for both Sequestration and Stocks. We felt that Biometric plots x sampling years and Flux Tower sites x sampling years should be weighted heavier than the other criteria (see Table 9) as measurements can be highly variable between and within sites, and between years. The applied weights would make the score out of 4 to correspond with the scoring system of the other evaluation categories. It is possible for a sequestration study to get an information reliability score greater than 4 if a study used both biometric and flux tower measurements. This is somewhat uncommon, but if it occurs only a max value of 4 can be given. We felt that if a study measured both biometric and flux tower measurements it should be acknowledged. Information reliability Scores less than or equal to 1 were automatically excluded from further consideration for the main database, but will be available in Appendix B.

Table 9: Weighting attributes to apply to points received from information reliability criteria (Table 8)

Category	Biometric plots x independent sites x years	Flux Tower site x years	Carbon Pools Assessed	Variables Measured
Sequestration	Points x 3.0	Points x 3.0	Points x 0.5	Points x 0.5
Stocks	Points x 3.0	Points x 0	Points x 0.5	Points x 0.5

A1.3 Relevance for Forests and Wetlands

Relevance evaluation was dependent on the study's proximity to southern Ontario ecoregions and species similarity to those found in southern Ontario. Specifically, ecoregions 6E and 7E in Canada (from Ontario GeoHub) or 8.1.x in United States (from the United States Environmental Protection Agency) (see Table 10). Relevance scores less than or equal to 1 were automatically excluded from further consideration for the main database, but will be available in Appendix B.

Table 10: Criteria used to evaluate Relevance for forest and wetland studies

Score	Description
4	a) Occurred within ecoregions 6E and 7E in Canada or 8.1.x in United States AND b) It is a forest or a wetland
3	a) Study was 1 ecoregion away from ecoregions 6E and 7E in Canada or in 8.1.x in United States AND b) Study focused on species in forests or wetlands which are dominant in ecoregions 6E and 7E in Canada or 8.1.x in United States
2	a) Study was 2 ecoregions away from ecoregions 6E and 7E in Canada or 8.1.x in United States AND b) Study focused on species in forests or wetlands which are dominant in ecoregions 6E and 7E in Canada or 8.1.x in United States
1	a) Study was 2 ecoregions away from ecoregions 6E and 7E in Canada or 8.1.x in United States AND b) Study focused on species in forests or wetlands which are occasionally found in ecoregions 6E and 7E in Canada or 8.1.x in United States
0	a) Study occurred in unclear location OR community type not specified OR ecozone very broadly described, e.g., eastern North America OR b) Location or community type not applicable to Ecoregion 6E or 7E or neighbouring ecoregions, i.e., more than 2 ecoregions away

A1.4 Source Reliability for Forests and Wetlands

Source reliability evaluation was mostly focused on the scrutiny a study was likely to receive before it was finalized. A secondary factor was the level of education the authors/supervisors had (see Table 11). Source reliability scores less than or equal to 1 were automatically excluded from further consideration for the main database, but are available in Appendix B.

Table 11: Criteria used to evaluate source reliability in forest and wetland studies

Score	Description
4	Peer-reviewed in reputable, non-predatory journal
3	PhD or MSc dissertation or significant research project undertaken by someone employed by a university and already obtained a PhD
2	Peer-reviewed in a possibly predatory journal or found in grey literature that is reputable or used for reputable purpose, e.g., our reports for ECCC
1	Website or other source that doesn’t meet criteria above
0	No information on source, e.g., not a primary study, but it is a reference to other work without providing a source

A1.5 Combining Scores and Converting to Confidence Labels

To produce the final scores for each study, the scores from the 3 sections (Information reliability, relevance, and source reliability) were added together and should range from 5 to 12 (relevance and source reliability have minimum scores of 2, information reliability has a minimum score of >1). For the ease of the NACAGT reader, we will then bin scores into easy-to-comprehend categories of high, medium, and low confidence (See Table 12 for binning categories.

Table 12: Converting the sum of information reliability, source reliability, and relevance scores into categorical confidence labels

Sum of Scores from the 3 Sections	Confidence Label
10.25 - 12	High
7.25 - 10	Medium
5 – 7	Low

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

A separate Microsoft Excel document can be made available upon request for additional information about carbon storage and sequestration for each land cover type. The document includes a breakdown of different carbon pools assessed by each source, and the confidence labels (see Appendix A for how confidence labels were produced). Appendix B also includes sources that we identified in literature review or data analysis, but did not include in the database (Tables 2 and 3 in this document) because of missing data or low confidence scores. Please email naes@cvc.ca to request access to this Appendix B spreadsheet.

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Appendix C: Ecological Land Classification Definitions

Table 13 below gives definitions to the Ecological Land Classification (ELC) codes used in the database (Tables 2 and 3). The definitions are mostly taken from Lee et al. (1998) along with some more recent interpretations.

Table 13: Ecological land classification codes and their definitions

ELC code	Name	Definition
MOS	Manicured open space	Large manicured open areas, not including buildings or paved areas. This code was used before the breakdown of the other manicured open space types, and is still sometimes found
MOI	Institutional open space	Large manicured open areas associated with institutional properties, not including buildings or paved areas
MOC	Commercial/industrial open space	Large manicured open areas associated with private commercial or industrial properties, not including buildings or paved areas
MOO	Other open space	Manicured open space not meeting the definitions of MOC, MOI, MOP, MOR
MOP	Private open space	Large manicured open areas associated with private residential ownership, not including buildings or paved areas
MOR	Recreational open space	Large manicured open areas associated with community centres, neighbourhood parks, greenspaces, gardens, sports fields, marinas, racetracks, ski hills, golf courses, etc. not including buildings or paved areas
CUM	Cultural meadow	An open area dominated by vegetation with less than 25 % tree cover, and less than 25 % shrub cover
CUH	Cultural hedgerow	A narrow strip of trees or shrubs (10 to 20 m wide) with either agricultural, urban, or meadow land use types on each side
FOC	Coniferous forest	Tree canopy is greater than 60 % of the land cover, and conifers make up greater than 75 % of that tree canopy
FOD	Deciduous forest	Tree canopy is greater than 60 % of the land cover, and deciduous trees make up greater than 75 % of that tree canopy
FOM	Mixed forest	Tree canopy is greater than 60 % of the land cover, and neither coniferous or deciduous trees make up greater than 75 % of that tree canopy
CUP1	Deciduous plantation	A planted area where tree canopy is greater than 60 % of the land cover, and conifers make up greater than 75 % of that tree canopy
CUP2	Mixed plantation	A planted area where tree canopy is greater than 60 % of the land cover, and neither coniferous or deciduous trees make up greater than 75 % of that tree canopy
CUP3	Coniferous plantation	A planted area where tree canopy is greater than 60 % of the land cover, and conifers make up greater than 75 % of that tree canopy

BOT	Treed bog	A bog where tree cover is between 10 and 25 %, and there is continuous Sphagnum species cover
FES	Shrub fen	A fen where tree cover is less than 10 %, and shrub cover is greater than 25 %
MAM	Meadow marsh	An area with seasonal flooding and less than 25 % tree and shrub cover. Usually dominated by grasses or sedges
MAS	Shallow marsh	An area with water less than two metres deep for most or all of the growing season. Usually dominated by emergent grasses or sedges
SWC	Coniferous swamp	An area with temporary or permanent surface water making up greater than 20 % of the ground coverage. Tree canopy is greater than 25 % of the land cover, and conifers make up greater than 75 % of that tree canopy
SWD	Deciduous swamp	An area with temporary or permanent surface water making up greater than 20 % of the ground coverage. Tree canopy is greater than 25 % of the land cover, and deciduous trees make up greater than 75 % of that tree canopy
SWM	Mixed swamp	An area with temporary or permanent surface water making up greater than 20 % of the ground coverage. Tree canopy is greater than 25 % of the land cover, and neither coniferous or deciduous trees make up greater than 75 % of that tree canopy
SWT	Thicket swamp	An area with temporary or permanent surface water making up greater than 20 % of the ground coverage. Tree canopy is less than 25 % and shrub cover is greater than 25 % of the land cover.
SAF	Floating-leaved shallow aquatic	Standing water is always present and less than two metres deep. Greater than 25 % of the surface of the water is covered in floating-leaved vegetation such as water lilies or duckweed
OA	Open aquatic	The entire area is water greater than two metres deep. There is no floating or submerged vegetation

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