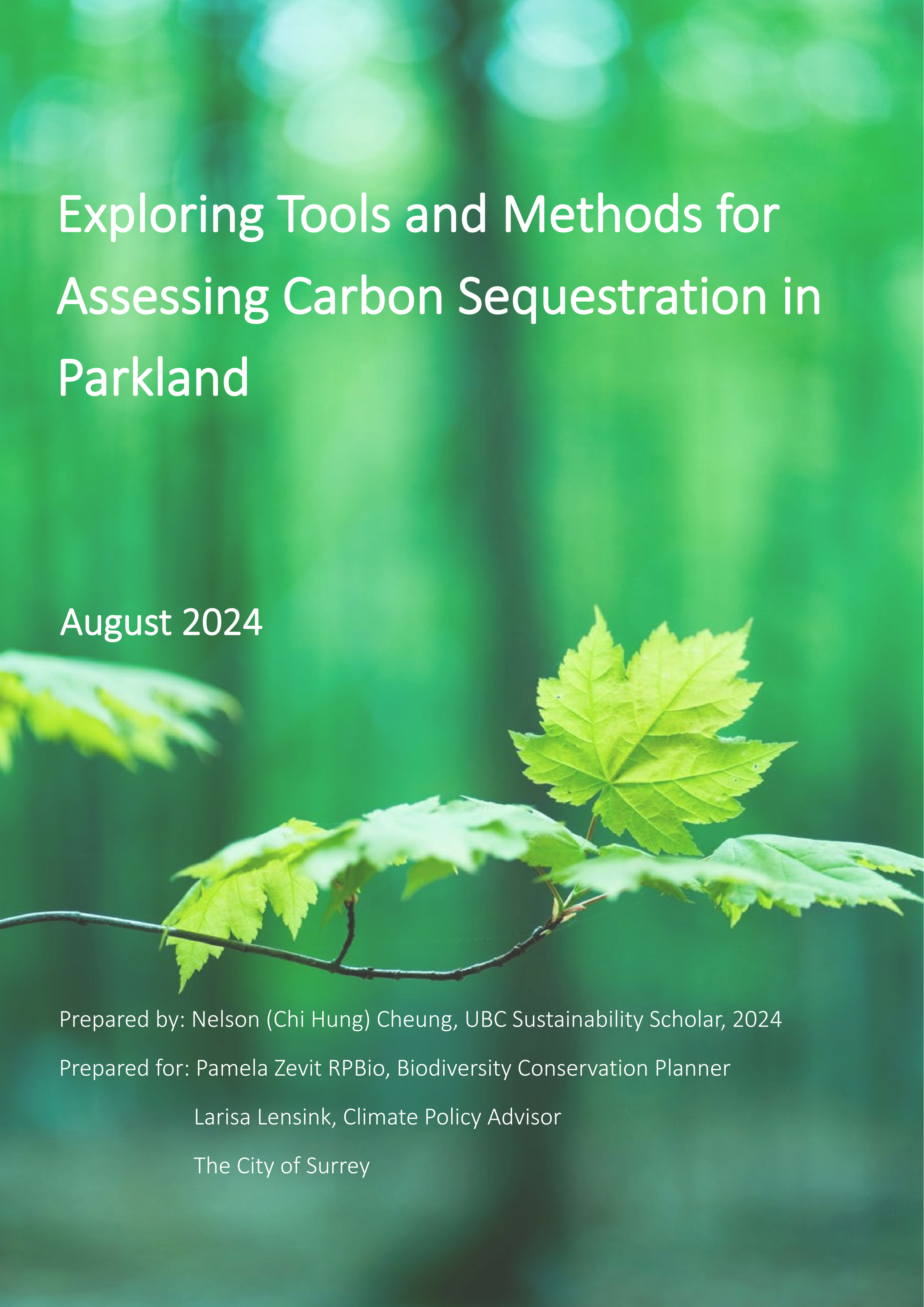

Exploring Tools and Methods for Assessing Carbon Sequestration in Parkland

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Disclaimer

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Executive Summary

In 2019, Surrey City Council declared a climate emergency, highlighting the urgent need for climate action. The city's diverse natural ecosystems, including forests, shrublands, streams, wetlands, and estuaries, are crucial for achieving carbon neutrality and enhancing climate resilience. This project aimed to research and evaluate tools and methods for assessing the carbon sequestration potential of these ecosystems within the City’s parkland to inform decision-making and facilitate effective management.

A literature review was conducted to understand carbon sequestration processes and prevalent assessment approaches, focusing on tools that are accessible and easily adaptable for city staff. Common practices in the region were also reviewed. A case study was performed on a selected parkland site using the most suitable tools based on available field data.

Several tools were identified, including ground-based measurement protocols, remote sensing techniques, and complex modeling approaches, each with specific strengths and limitations. The InVEST carbon model proved effective for general estimates, while the CBM-CFS3 model, suited for Canadian forests, is better for detailed analysis but requires more data and expertise. It is recommended that the City use field measurements to tailor assessments to specific ecosystems, validate results, and support methodology development.

In summary, while no single tool is universally applicable, a combination of various tools and field data will enable more accurate and flexible carbon sequestration assessments, supporting the City's climate goals.

1 Introduction

Since the Industrial Revolution, human activities have caused excessive emissions of greenhouse gases (GHGs) and disrupted the Earth's climate equilibrium, driving climate change, now a major challenge to life on our planet. Carbon dioxide is the most commonly produced greenhouse gas contributing to climate change. The release of excessive carbon dioxide into the atmosphere, primarily through combustion of fossil fuels, has warmed the planet at an unprecedented rate, leading to long-term changes in temperature and weather patterns, adversely affecting the livability of cities and the health and safety of their inhabitants. As a global effort, The Intergovernmental Panel on Climate Change has produced reports recommending actions to limit global warming to 1.5°C above pre-industrial levels[1]. With the intensifying effects of climate change, governments at different levels have set their own goals to reduce greenhouse gases emissions and achieve carbon neutrality. Maintaining or enhancing carbon sequestration and storage in natural ecosystems is now increasingly identified as a cost-effective nature-based solution providing various co-benefits for climate resiliency. With concerted protection, restoration and management, these ecosystems can act as significant carbon sinks helping to alleviate the impacts of climate change[2].

To better manage natural ecosystems and achieve carbon neutrality goals, cities need carbon quantifying tools and methods to support decision-making, particularly for activities involving or impacting these systems. Carbon quantification, often associated with carbon accounting, involves measuring the amount of carbon in various pools and fluxes within ecosystems, as well as greenhouse gas emissions (primarily carbon dioxide) from both natural and anthropogenic sources. The principles of carbon accounting are similar to those used in financial asset management, which is why the term 'natural assets' is commonly used to refer to natural ecosystems and greenspaces.

While senior governments may provide over-arching frameworks and guidelines, it is a challenging task for local governments to perform carbon quantification, as they have to consider the complicated interactions between and within their natural ecosystems on a finer scale with limited resources. Nevertheless, an array of tools is now available either open-source or proprietary, thanks to the advancement in modern analytics. These tools, based on different assumptions, have strengths and weaknesses depending on their applications.

1.1 Surrey Context

As the largest city by land area in Metro Vancouver and second most populated in British Columbia (BC), the City of Surrey has over 2800 hectares of parkland with more than 1700 hectares of natural areas[3]. Surrey is endowed with a diversity of natural ecosystems, including forests, shrublands, streams, wetlands and estuaries. Facing the dual stressors of climate change and a fast-growing population, there are still opportunities (and challenges) in managing these natural assets to achieve various sustainability goals.

In 2019, Surrey's City Council declared a climate emergency, recognizing the urgent need for climate action. Interim and long-term targets in cutting carbon emissions and a roadmap of actions to be taken have since been laid out in its Climate Change Action Strategy (CCAS)[4]. The targets for community emissions are to reduce GHG emissions from non-agricultural and non-industrial activities by 45% by 2030 compared with 2010 levels and achieve net zero before 2050. "Climate-Positive Resilient Ecosystems" is identified in the CCAS as one of the critical areas in reducing emissions and improving resiliency to climate impacts, including increasing the ecosystem service of carbon sequestration. Apart from CCAS, the City also has several progressive policies that aim to protect its ecosystems, supporting carbon sequestration.

The Biodiversity Conservation Strategy (BCS)[5], although focusing on habitats and their connectivity, is highly complementary to CCAS. The protection of ecosystem integrity through enhancing and restoring habitats as well as controlling invasive species, will also benefit the enhancement of carbon sequestration. The Green Infrastructure Network, which is detailed in the BCS, helps to outline the connectivity of habitats by identifying important habitat hubs, sites and corridors. This not only facilities conservation efforts but informs decision making on land use planning. Contributing to improving overall ecosystem health and thus carbon sequestration potential.

Building on the existing plans and policies in tree and natural areas protection and enhancement, the City's Urban Forest Management Strategy[6] recognizes the ecosystem services, including carbon sequestration, provided by the City's urban forest. Its goals to stop the citywide decline in tree canopy cover and to achieve a 30% canopy cover target by 2038 (lands in the Agricultural Land Reserve were exempt from this analysis), are intrinsically linked with conservation of the City's biodiversity and related ecosystem services.

Moreover, the City has developed a Coastal Flood Adaptation Strategy[7] to reduce the impacts of climate change and sea level rise. While the primary goal of the strategy is to enhance resilience against flooding in the city's coastal lowlands, it also provides opportunities for conserving its diverse aquatic ecosystems. The Mud Bay Foreshore Enhancements project is a great example that demonstrates the potential of a "living dyke" not only in providing flood protection but also in generating ecological co-benefits from the established salt marsh. A living dyke is created by adding sediment and planting native salt marsh species to establish a gentle, raised slope. This helps natural marshes keep up with sea level rise[8]. This nature-based approach can be adopted to identify other ecosystems such as freshwater wetlands and riparian areas, that should be conserved and enhanced to provide flood protection and other various ecosystem services, such as carbon sequestration.

These strategies undeniably constitute integral components of the overarching objective to mitigate climate change, based on the common premise that well-functioning ecosystems provide essential services. Ecosystem services are often delivered simultaneously, highlighting the interconnectedness of natural processes. Therefore, promoting carbon sequestration through ecosystem maintenance and enhancement can yield co-benefits such as enhanced biodiversity, increased canopy cover, and improved flood and stormwater mitigation. Additionally, these benefits can also support carbon sequestration efforts. Incorporating the concept of carbon sequestration into these strategies is both possible and essential for advancing holistic climate actions in the city, through considering vegetation communities, habitat conditions, and effectively reducing ecosystem stressors.

The City is aware of the need for tools/methods to better quantify and maximize carbon sequestration, which is identified as one of the actions in the CCAS. However, a systematic approach is required to assess and evaluate the efforts of promoting carbon sequestration. Therefore, a review of accessible tools will benefit the identification of suitable, up-to-date approaches that address the City's specific needs and constraints.

1.2 Scope and Objectives of the Study

With an aim to gain an understanding of the tools available for assessing carbon sequestration potential and application of those tools/methods in planning and management of natural areas and green infrastructure in parkland in the City of Surrey, the study has the following objectives:

1. Identify and recommend available tools to quantify carbon sequestration potential of various ecosystems.
2. Understand the tools/methods used to quantify and enhance carbon sequestration being implemented by other municipalities.
3. Identify opportunities to incorporate carbon sequestration potential within the City's policies.

The study focused on identifying tools that are freely available and widely used in academic and/or operational areas. Particular attention was given to approaches that can be easily adapted by city staff and applied in the city's context. Time and capacity constraints meant field work was not able to be carried out during the project but field data from previous studies has been used in testing the tools/methods.

1.3 Research Approach

1.3.1 Literature Review

A review of academic literature, grey literature, and government reports was conducted to gain an understanding of the current knowledge on carbon sequestration in various natural ecosystems. Focus was particularly placed on research studies relevant to common ecosystem types found in the City of Surrey. Tools/methods used by various organizations to quantify carbon sequestration potential of natural ecosystems were also identified throughout the process. While the identification of tools/methods was conducted from an international scope, special attention was given to approaches used in North America, especially in areas which were geographically and ecologically similar to the City of Surrey. Only tools/methods that were regularly updated, well documented, and freely available, were further evaluated for application in the context of the City of Surrey.

1.3.2 Personal Communication

A best practice review was also conducted to identify tools/methods used by other jurisdictions within BC. This involved direct communication with government staff through email exchanges and interviews to obtain detailed information about their studies and methodologies in quantifying carbon sequestration. Additionally, non-governmental organizations and governments outside of BC were consulted to leverage their experience and approaches in relevant areas.

1.3.3 Case Study

A case study was performed on a selected park site in Surrey, chosen for its representative ecosystem types and the availability of relevant field data. The methodology, findings and learnings from applying the tools into practice were documented to help identify opportunities to incorporate consideration of carbon sequestration potential within the City's policies and processes.

2 Background Knowledge

2.1 Carbon Sequestration and Storage as Ecosystem Services

In order to develop appropriate carbon quantifying approaches and holistic management practices for our natural ecosystems, it is essential for us to understand them and appreciate their importance in the context of ecosystem services. Ecosystem services are various direct and indirect benefits that healthy ecosystems provide to support wellbeing and quality of life for human societies. They are typically classified into four main categories, supporting, regulating, provisioning and cultural[9] (Figure 1).

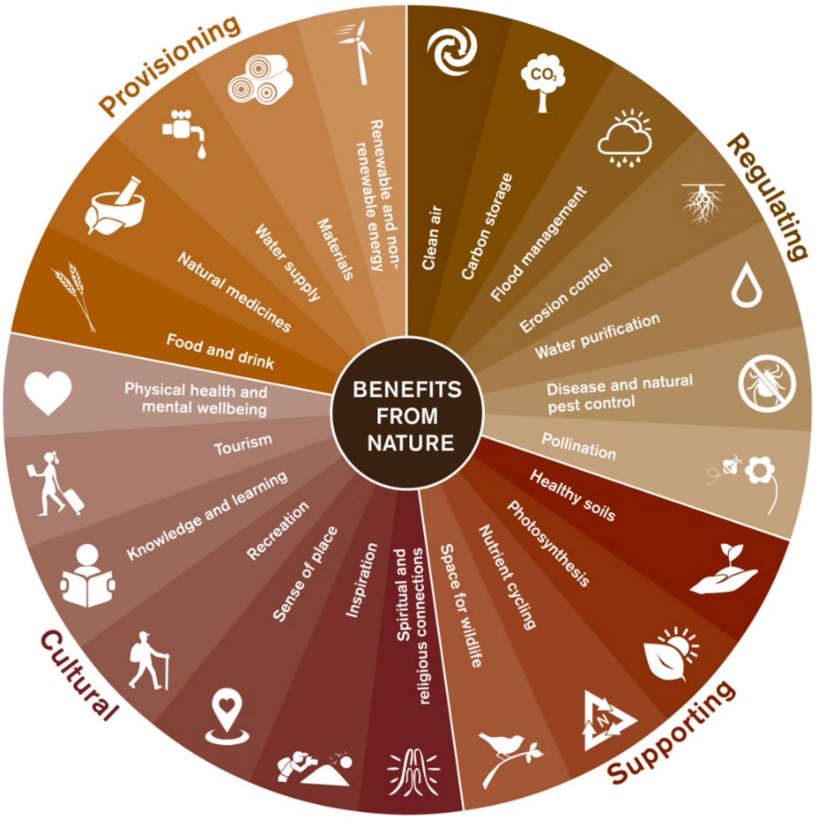


Figure 1. Ecosystem services and benefits received by humans in the form of security, goods and materials, health and wellbeing (Source: NatureScot, Scotland's Nature Agency, 2023)

Carbon sequestration and storage are crucial mechanisms within the regulating services that help mitigate climate change by reducing atmospheric carbon dioxide concentrations. Although the two terms are often used interchangeably, they refer to distinct but closely related processes. Carbon sequestration encompasses both natural and deliberate processes by which carbon dioxide is either removed from the atmosphere or diverted from emissions sources and stored in the ocean, terrestrial environments (vegetation, soils, and sediments) and geologic formations[10]. In contrast, carbon storage pertains to the retention of sequestered carbon in various pools over time. While this study broadly uses the term "carbon sequestration", it inherently includes the concept of carbon storage. Understanding these nuances is essential, particularly when employing tools and methods to quantify carbon content in ecosystems.

In ecosystems, carbon sequestration primarily occurs through the process of photosynthesis, whereby plants absorb carbon dioxide from the atmosphere and use it to build their biomass in foliage, stems, branches and roots. Carbon is stored in their tissues as plants grow. When plants die and decompose, some of the carbon is transferred to the soil, where it can be stored for varying durations before being released back to the atmosphere. Therefore, the buildup of biomass, whether it is in living or decaying organic matter, is a key component of carbon sequestration.

Maintaining and enhancing ecological communities promotes the buildup of biomass, furthering carbon sequestration and storage. A diverse, well-functioning ecosystem offers a range of benefits beyond just carbon sequestration. It can enhance biodiversity and resiliency, improve water quality, protect coastal areas from flooding, mitigate the urban heat island effect, and enhance recreation and aesthetic values. Thus, the importance of carbon sequestration becomes more apparent when we recognize its interconnectedness with various ecosystem services.

2.2 Factors Affecting the Carbon Cycle

In nature the carbon cycle involves intricate interactions between various pools and fluxes, which can be significantly altered by human activities. To make accurate estimations of carbon sequestration potential of ecosystems, it is crucial to have a thorough understanding of the factors influencing these processes. Although carbon quantifying tools are useful, they necessarily simplify the complex dynamics of the real world. The multiple physiochemical and biological processes that regulate the cycle can add further layers of complexity to our efforts in measuring and managing carbon.

The global carbon cycle is a dynamic system that governs the movement of carbon in the Earth's system (Figure 2). It plays a crucial role in regulating the Earth's climate and sustaining life on earth. Carbon dioxide is absorbed by vegetation through photosynthesis, converted into different forms of biomass (above and below-ground), dissolved in open water and incorporated into the soil. In contrast, carbon dioxide is released back to the atmosphere, through vegetation and soil respiration, decomposition of deadwood and litter, and ecosystem disturbances such as pests, wildfire, deforestation and anthropogenic land use changes. Human activities and climate change can impact this cycle. While soil degradation and removal can release stored carbon into the atmosphere and reduce future carbon storage capacity, investing in green infrastructure, such as enhancing the extent and structural diversity of urban forests, or incorporating raingardens and other engineered wetland features can help mitigate some the negative impacts of development.

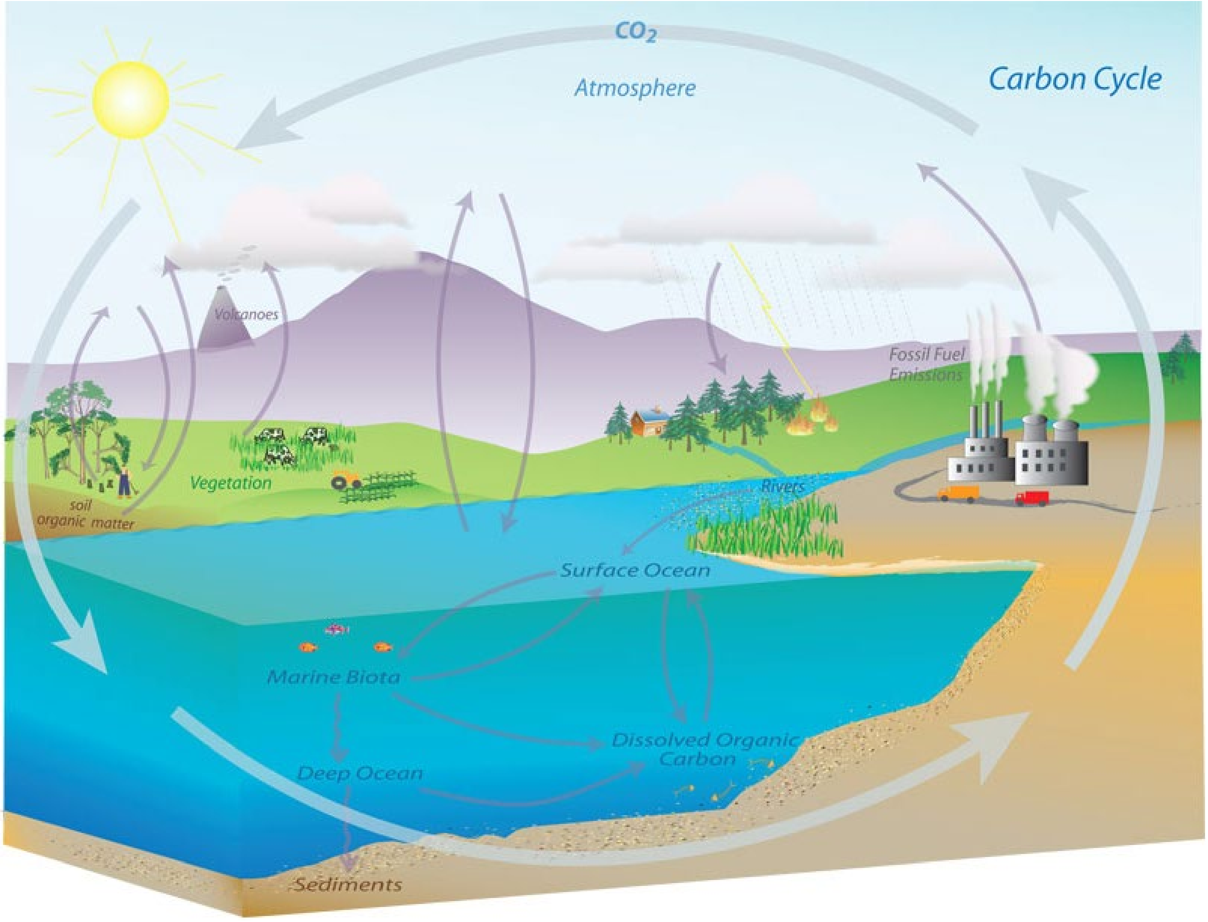


Figure 2. The global carbon cycle (Source: National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 2019[11])

Climate change can also affect the growth rate of vegetation, and subsequently carbon sequestration capacity by extending the growing season[12]. Similarly, carbon boosting effects from rising temperature and carbon dioxide concentrations can also occur in soil, involving the complex interactions of water and nutrients availability[13]. Conversely, biodiversity loss induced by climate change and land-use changes can be detrimental to ecosystem integrity and thus the potential of these systems for carbon sequestration and storage[14]. All these processes interact and occur at different rates based on the ecosystem type and disturbances. Therefore, it is necessary to consider these dynamics when assessing and evaluating the carbon sequestration potential of natural ecosystems.

2.3 Carbon Sequestration in Various Natural Ecosystems

While local and global factors influence the carbon cycle in natural ecosystems, these factors also cause variations in the amount of carbon stored and transferred across different pools. The City of Surrey's Park system supports a diverse range of ecosystems. Understanding the distribution of carbon across these ecosystem types is essential for estimating their carbon sequestration potential and evaluating the effectiveness of various tools and methods.

2.3.1 Forests

Surrey's urban forests, including natural forest communities and street trees, cover 29% of the City. Forests have long been a primary focus of global carbon sequestration efforts due to their significant role in capturing and storing carbon. While different classifications may be used, carbon pools in forest ecosystems are generally grouped into living biomass, dead biomass (e.g., dead wood, roots, and litter) and soil organic matter (Figure 3).

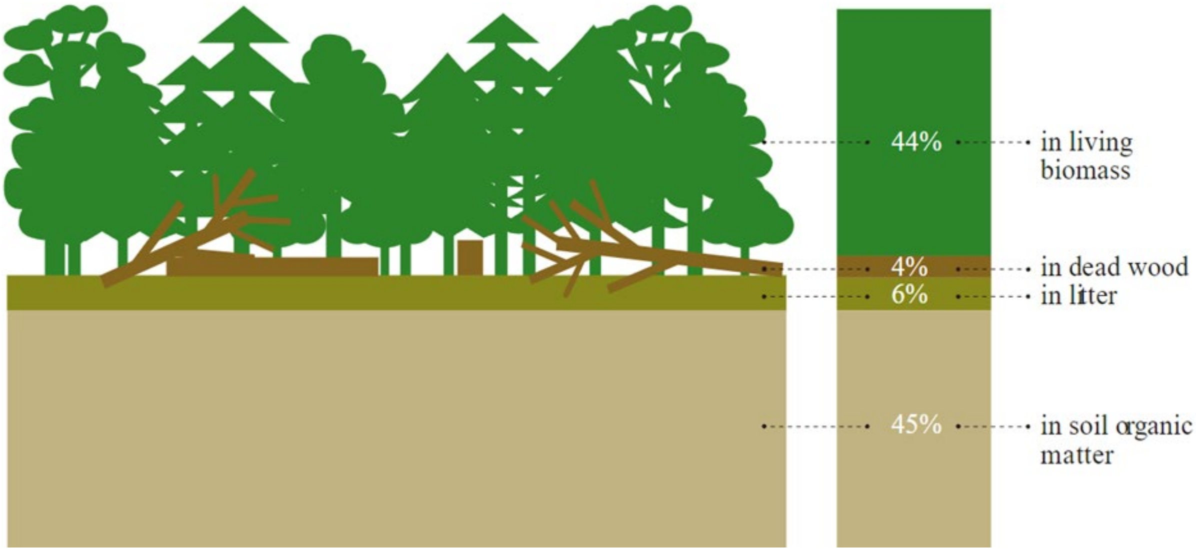


Figure 3. Proportion of carbon stocks in various carbon pools in forest ecosystems (Source: Food and Agriculture Organization of the United Nations (FAO), 2020[15])

Living biomass and soil organic matter are two major carbon stocks in forests. Their ratio can vary in different forest types. Soils store more carbon than the living biomass in temperate and boreal forests, while the ratio between the two stocks are relatively the same in tropical forests[16]. Coniferous and deciduous forests can exhibit different rates of carbon sequestration due to variations in growth rates and species composition. A recent study in the UK projected that fast-growing coniferous plantations (Sitka spruce) capture more carbon than broad-leaf species (Birch and oak) within the first 30 years. However, the difference diminishes over the long term[17]. Conversely, research in Lativa indicates that the annual carbon sequestration rates are higher in both mature and old-growth stands of birch and European Aspen compared to Scotch pine and Norway spruce[18].

It is also commonly believed that the carbon sequestration rate of forests tends to decline as forests age with tree growth levels off over time. Whether old-growth forests have reached a state of equilibrium (zero net change) in carbon sequestration is still a topic of debate[19]. Regardless these forests remain significant carbon reservoirs and are crucial for the provisioning of other ecosystem services. True old-growth forests (Forests on BC's Coast and in the Interior wet belt are considered old growth if their trees are more than 250 years old[20]) rarely occur in most urban areas due to various anthropogenic disturbances.

The inclusion of below-ground soil carbon pools can add extra complexity to the discussion. Soil moisture, types and structures all influence the duration of carbon storage in soils. Generally, carbon pools in upland forest soils are considered relatively stable compared to those in waterlogged areas, such as forest swamps, where changing water tables can introduce more variability. In forested areas that are consistently inundated with freshwater, the anaerobic (lack of oxygen) conditions slow down soil microbial activity, which can lead to lower decomposition and thus higher carbon accumulation. It is not uncommon to find forest swamps on floodplains, which constitute about 20% of the land area in Surrey. Identifying and studying these forest swamps is also critical for accurately reflecting the carbon sequestration potential of the forest ecosystems[21].

2.3.2 Terrestrial Wetlands

The City of Surrey boasts a rich array of freshwater assets including streams, lakes and wetlands. Wetlands can serve as significant carbon sinks, storing most of their carbon in the inundated soil where it is protected from decomposition[22].

Other than forested swamps, terrestrial wetlands, are relatively easier to identify because they are not obscured by forest cover. These wetlands can host a variety of plant communities, ranging from graminoid-dominated marshes and woody shrubs with Sphagnum moss in bogs, to sedges and grasses in fens[23]. The peat layer in bogs and fens can store a vast amount of carbon, while peat formation is less common in swamps and marshes. The interaction between plant communities and the wetlands' hydrology plays a significant role in their carbon sequestration capacity. Draining and reclamation of wetlands causes substantial carbon emissions and loss of ecosystem services. These anthropogenic disturbances also release methane, which is produced and stored in wetlands and is a more potent greenhouse gas than carbon dioxide[24].

In the City of Surrey, marshes are the most common type of wetland, followed by bogs. Restoration of wetland areas may also involve the creation of constructed or engineered wetlands, where the carbon dynamics may differ from their natural counterparts depending on the design and the management practices such as cyclical removal of accumulated sediments and vegetation.

2.3.3 Meadows and Old Fields

The City of Surrey has a considerable number of parks supporting woody shrubs, herbaceous plants and grass cover. These ecosystem types typically develop from forest clearing or because of environmental constraints or human activities. Many of these are old-field areas, previously used for agriculture that remained unmanaged and fallow long enough to develop natural meadow or grassland and shrub thicket characteristics.

Similar to natural grasslands, most of the carbon in these grass-dominated ecosystems is stored below ground. Carbon is fixed primarily in the deep and extensive root systems of grasses. Root turnover and decomposition contribute to the soil carbon pool by adding organic matter. With minimal disturbance, this carbon can be stored underground for extended periods.

However, the establishment of invasive species, such as Himalayan blackberry, in these open habitats can disrupt native plant communities and affect their climate resilience and carbon sequestration capacity. In contrast, natural succession and tree plantation following forest clearing or disturbances can increase the amount of carbon stored in aboveground biomass.

2.3.4 Coastal Ecosystems

With three major estuaries and nearly 20 kilometers of direct coastline, Surrey includes a diversity of marine ecosystems, found in Boundary Bay, Mud Bay, and Semiahmoo Bay. This area is part of the internationally designated Fraser Estuary Key Biodiversity Area. These ecosystems include intertidal mudflats and shallow water areas dominated by seaweed and eelgrass, as well as estuarine marshes characterized by salt-tolerant plants.

Because of its proximity to the ocean, carbon stored in these ecosystems is often termed as "Blue Carbon". Coastal ecosystems store most of the carbon in soils or sediments under their plant communities. Carbon dioxide captured by plants can eventually be stored in the soil for hundreds of years or longer, due to the very slow decomposition from the largely anaerobic conditions (Figure 4). Carbon in seagrass can be stored in sediments up to six meters under the seabed. It is estimated that conservation of seagrass ecosystems worldwide could save up to 650 million tons of carbon dioxide emissions annually[25].

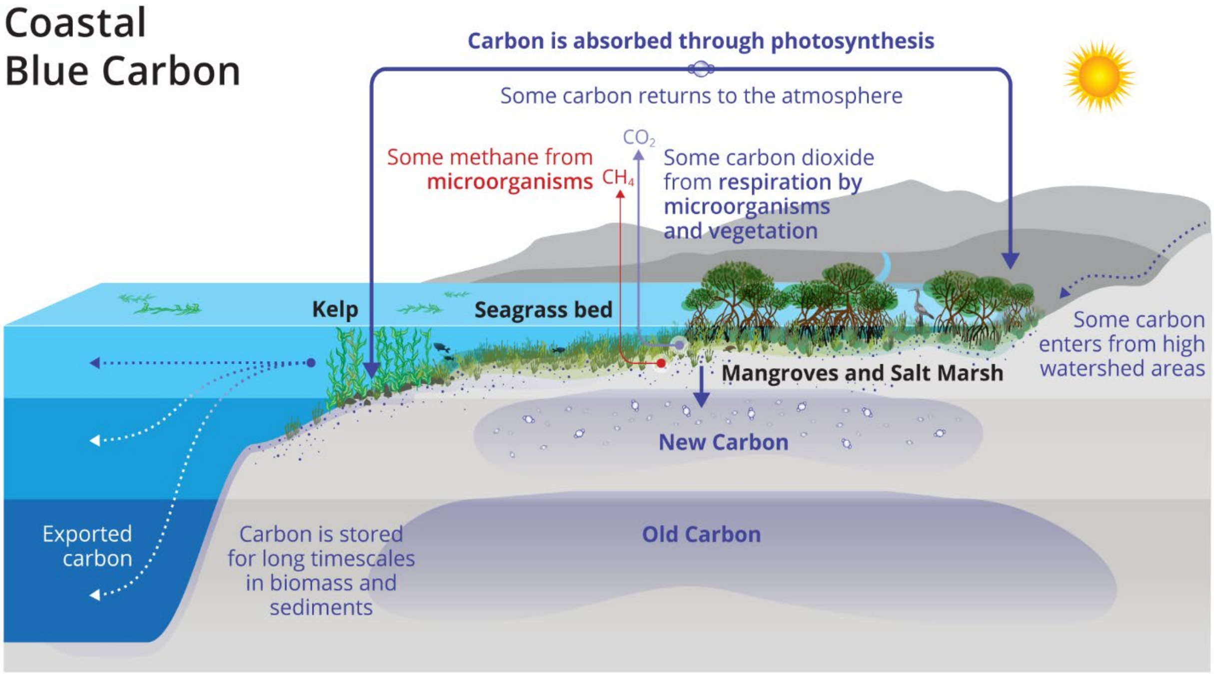


Figure 4. Pathways of carbon in coastal ecosystems (Source: NOAA Climate.gov[26])

Located along the coastline, these ecosystems can also trap carbon-rich upland sediments transported downstream by rivers[27]. Subsequently coastal ecosystems not only absorb atmospheric carbon dioxide but also retain carbon lost from other ecosystems in the form of degrading biomass and dissolved carbon.

3 Common Approaches and Tools Available

With advancement in knowledge and technology, a variety of tools or methods have been developed to quantify carbon sequestration potential of natural ecosystems. These tools can vary in scale, input data requirements and complexity, and are often tailored to specific ecosystem types. However, certain approaches, or combinations of them, are used in common practice to capture carbon dynamics.

3.1 Field Measurement

Field measurement is a traditional yet indispensable method for quantifying carbon stocks in natural ecosystems. This approach involves obtaining field data through various techniques, such as soil sampling, vegetation surveys, and litter collection. Once collected, carbon content is determined through laboratory analyses. Long term and regular field measurements, particularly on the same plot, allow for the establishment of trends over time in carbon stocks. Additionally, specialized equipment such as “eddy covariance” instruments can measure the net ecosystem exchange of carbon dioxide in real time, providing valuable insights into the carbon sequestration potential of the area being assessed.

3.1.1 Field Data-driven Tools

Beyond direct measurement, field data is crucial for determining future carbon estimates. In forest research, traditionally driven by silviculture practices, growth equations have been developed and used extensively. These empirically derived equations enable the estimation of carbon stocks using basic field data, such as tree height and diameter at breast height (DBH). By incorporating the results of these equations into models, researchers can simulate ecosystem dynamics and project changes in carbon stocks.

In Canada, both the federal and provincial governments have been utilizing forest inventory data to develop empirical volume to biomass conversion equations/models to support assessment of carbon sequestration in forest ecosystems[28] [29]. In conjunction with theoretical models, the BC provincial government has developed tools such as the Table Interpolation Program for Stand Yields (TIPSY) and Variable Density Yield Projection (VDYP) to facilitate management of both managed and natural forest stands[30]. Although these tools were primarily developed for timber supply prediction, they can be used to estimate forest volume, biomass and consequently carbon stocks. The user-friendly interface of their desktop applications allows users to input basic data, such as tree species, age, density and basal area as well as crown closure, to generate graphical and tabular outputs that project carbon stocks in above-ground biomass over time.

In the US, the USDA Forest Service and its partners have developed i-Tree, an analysis tool become widely used globally[31] . i-Tree is a suite of software applications that provides analysis and ecosystem services benefit assessments primarily for urban forests at various scales. i-Tree was developed using both empirical equations and models integrating environmental and location variables. It allows users to assess ecosystem services provided by urban trees, including carbon sequestration and storage. The depth of the analysis in i-Tree depends on the specific methodologies employed by each tool in the suite. The flagship tool “iTree Eco”, requires a minimum tree species and DBH data to run. One disadvantage of i-Tree is that it cannot estimate soil carbon stocks.

Fieldwork allows for direct carbon assessment but is resource intensive. Despite this, it is essential for providing baseline data for developing and validating tools and methods to estimate carbon sequestration potential. High quality field data often results in more accurate and reliable estimates, making them a critical component of effective carbon monitoring and management.

3.2 Remote Sensing

Remote sensing data, combined with ground-based measurements, are now widely used to assess carbon sequestration in ecosystems, especially when large-scale, detailed spatial and temporal information is needed. Aerial imagery and airborne sensors, such as LiDAR (Light Detection and Ranging), are among the most common techniques employed in these practices.

Aerial photos, including orthophotos (which are geometrically corrected to address distortion and ensure scale consistency), are optical images that capture and represent the intensity of light reflected from the Earth’s surface across different wavelengths. These images allow the derivation of various vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), which can be applied to assess vegetation density, types, and health. Researchers have developed various approaches, depending on the image resolution, to use these indices and ground-based data for estimating above-ground biomass and carbon storage. Laser sensors, such as LiDAR, can capture the three-dimensional characteristics of vegetation and provide additional information beyond what aerial photos offer. For instance, tree heights can be derived from LiDAR data and used in allometric equations (measuring changes in size) to estimate tree age, biomass and thus carbon stocks. Detailed classification of land uses and cover can also be achieved using these remotely sensed data, as well as changes which can affect carbon sequestration potential of ecosystems.

The use of remotely sensed data has gained popularity due to its ability to provide rapid assessments across various scales. Numerous studies have been conducted worldwide to estimate ecosystem carbon sequestration, using both remotely sensed and ground-based data. Deep machine learning techniques are also increasingly employed[32] . However, accuracy can vary depending on data quality and vegetation structures. Also, ground truthing is necessary to ensure the reliability of these estimations.

The natural capital project[33] , led by Stanford University and its collaborators, has developed a series of software models known as the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). The InVEST carbon model provides a user-friendly interface that uses user-defined carbon stock values together with a user-provided land cover map to estimate carbon storage in a specific area. Carbon sequestration potential can be estimated when a future land cover map is provided to reflect the changes in land use and cover. Coastal ecosystems can also be assessed using the coastal blue carbon model in a similar fashion. Although the models do not simulate ecosystem dynamics, they provide a flexible, simplified and fast spatial assessment. The accuracy of the models depends on the land cover map resolution and user-defined carbon values for various land covers.

3.3 Modeling

While ecosystem attributes, such as vegetation cover, can be assessed through field measurements and remote sensing techniques, these data are often historical and only reflect a snapshot in time, especially when continuous measurements are not feasible. Consequently, scientists have developed various models to predict the dynamic, ongoing changes in ecosystems. Among these, process-based models are the most commonly used. A process-based model is the mathematical representation of physical, chemical and biological processes that characterize the functioning of ecosystems[34] . This kind of modeling is particularly useful for evaluating the impact of disturbances and changing environments on the carbon sequestration potential of ecosystems.

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)[35] is a well-known carbon accounting model developed by the Canadian federal government (Figure 5). The model can be used to estimate carbon stocks and stock changes for both stand and landscape level forest ecosystems, including foliage, stem wood, roots, litter, snag and soil carbon pools. The impact of various disturbances, such as pests, fire, and planting, can be simulated in the model. Growth (volume-to-age) curves of tree species are needed for projection of changes in carbon stocks. In the context of Canadian forests, these curves can be generated using the growth and yield models developed the BC government (see section 3.1.1). However, CBM-CFS3 is a model that does not explicitly account for the spatial distribution of forest stands. In contrast, its sister model, the Generic Carbon Budget Model, is spatially explicit and incorporates geographic information for detailed spatial analysis. Using the Generic Carbon Budget Model requires knowledge of Python scripting, which involves writing instructions for the computer in the Python programming language.

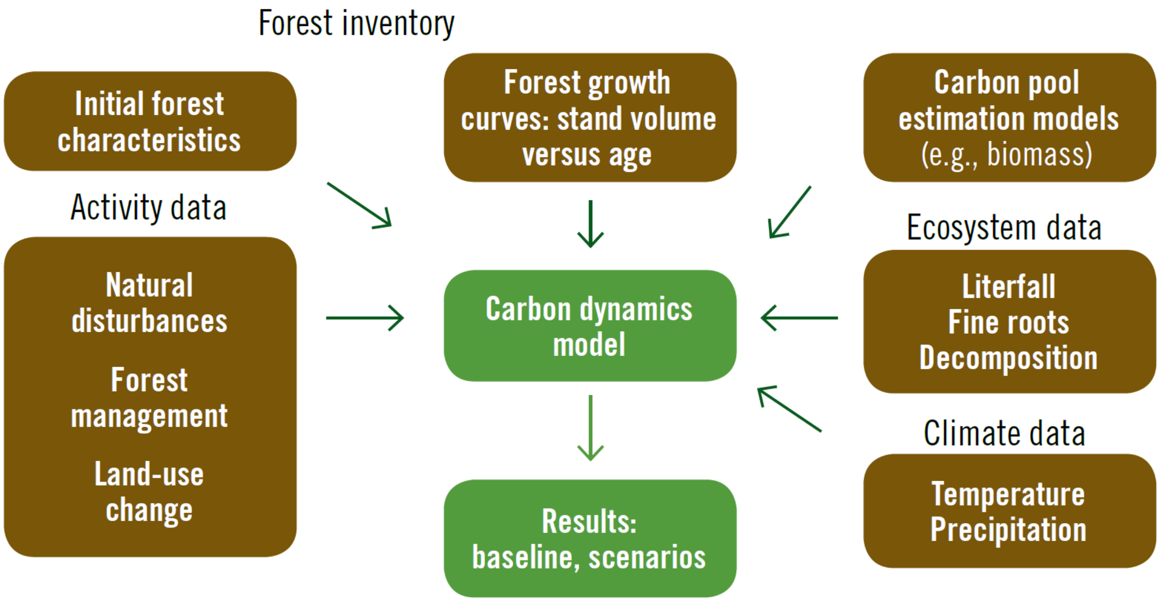


Figure 5. Input requirements of CBM-CFS3 (Source: Kurz et al., 2016[36])

The USDA Forest Service has also developed forest growth simulation models known as the Forest Vegetation Simulator (FVS)[37] , which operates on individual tree and stand levels. FVS can be used with its Fire and Fuels Extension to estimate carbon stocks in various forest stand components. It has a geographic variant for BC, that are calibrated for major tree species within BC. Impact of disturbances caused by insects, disease and fire can be simulated in the model as well. However, soil carbon pools are not included in FVS.

These models simulate an ecosystem's dynamics and support decision-making by providing scenario analysis. Using results from these models, look-up tables can be created to facilitate general and average estimations of carbon stocks in different carbon pools within forest ecosystems. The USDA Forest Service has produced a series of lookup tables for both natural and plantation forests using various models[38] [39]. These tables relate forest age to volume and carbon density in components ranging from aboveground biomass to soil organic matter. Although these carbon stock values are regional estimates and their accuracy may be uncertain, they are valuable for rapid assessments, especially when field measurement and detailed modeling are not possible.

In addition to forest ecosystems, several process-based models have been developed by scientists to assess carbon sequestration and/or greenhouse gas fluxes in wetland ecosystems[40] . While these models offer valuable insights, they are generally more complex to operate and require extensive input data, including water temperature and hydrological properties specific to wetlands. The Blue Carbon Calculator (spreadsheet) developed by the Massachusetts government[41] , US, provides an easy method to calculate carbon and methane emissions from soils resulting from wetland management activities. The calculations are based on lookup tables with values referenced from The Intergovernmental Panel on Climate Change (IPCC) and literature estimates. However, it is only applicable to wetlands restoration projects and the calculations are rather generic.

With advancements in ecosystem knowledge and ongoing refinement of existing models, it is anticipated new tools will be developed. Currently, a variety of tools and methods with differing levels of complexity have been developed to assess ecosystem carbon sequestration. Their application often involves a trade-off between resource availability to implement and desired output accuracy. A summary of common tools and methods that are publicly available and relatively easy to use, and their strengths and limitations, is included in Appendix A.

4 Common Practices in the Metro Vancouver Region

As awareness of climate change and the importance of ecosystem services grows, assessing carbon sequestration is becoming increasingly common in urban areas. However, the field is still developing and tends to focus on specific types of ecosystems, such as urban trees. In Metro Vancouver, relevant studies conducted by various jurisdictions remain limited, though there are ongoing efforts to address this.

4.1 FORECAST Model

Among the existing studies identified through government websites or personal communications with government staff, the FORECAST model was used in several projects to estimate carbon stocks and project stock changes in forest ecosystems. FORECAST is a hybrid forest growth model that employs both empirical and process-based modeling techniques to simulate forest dynamics and predict changes in forest ecosystems[42].

The Metro Vancouver Regional District (MVRD) has commissioned the development of a regional carbon storage dataset for its various ecosystems, using the FORECAST model in combination with other tools[43]. The carbon storage dataset (2019) is presented in the format of an ArcGIS file (Geodatabase), where both soil and biomass carbon are summarized in the level of property parcels. Biomass carbon density was calculated using above-ground biomass data for areas covered by the BC provincial vegetation resources inventory (VRI). Meanwhile, soil carbon density (excluding agricultural soils in the City of Delta) was generally represented by an average value generated by the FORECAST model. For areas lacking VRI data, particularly major urban areas in the southern part of the region, LiDAR data and land cover classification were used instead. In these areas with forest ecosystems, LiDAR data were used to derive the tree height, which was then used to estimate the tree age with general height-age curves. Subsequently, both biomass and soil carbon densities were determined using age-indexed lookup tables generated by the FORECAST model. Non-forest ecosystems with significant carbon storage were identified using the Sensitive Ecosystem Inventory (SEI) dataset. These included estuarine, intertidal, wetland, and riparian ecosystems.

The methodology adopted by the MVRD government demonstrates a relatively quick assessment approach to carbon storage by utilizing the best available datasets. With many cities now having LiDAR coverage, deriving tree heights from LiDAR data can be quite doable using GIS software. However, the general classification of trees into coniferous and deciduous may not accurately reflect the characteristics of specific tree species, particularly for a finer scale project. Additionally, retrieving suitable carbon values from the literature for some non-forest ecosystems can be challenging.

The City of Richmond has also completed a carbon credit quantification project (2019), using field data, the FORECAST model and an Excel-based Landscape Summary Tool. The project assessed the greenhouse gas emission reduction, as reflected by carbon storage and emissions in different components in a scenario analysis, over a 19.8-hectare bog ecosystem (part of the Lesser Lulu Island bog)[44] . Changes in carbon storage in forest and other vegetation biomass was projected using the FORECAST model and greenhouse gas emission from peat layer was calculated separately. While the same model was employed, the modelled carbon storage in this project was verified and supported by field measurements including tree surveys, soil carbon analysis and hydrological analysis.

Modeling combined with field measurements is currently one of the most comprehensive approaches for assessing carbon sequestration potential of ecosystems. The FORECAST appears to be a promising model, providing estimations of carbon stocks that are comparable to those of CBM-CFS3. However, the FORECAST model was used by the consulting company in those studies, and its official website is no longer available, while the most recent published research paper on the model dates to the early 2010s. As a result, accessing the model and staying updated on its development over time is difficult.

4.2 i-Tree

As part of their urban forest management efforts, municipalities in Metro Vancouver commonly use the i-Tree software suite to evaluate total tree canopy cover, as well as to estimate carbon sequestration and storage in urban forests. While i-Tree Canopy is frequently used, some cities used i-Tree Eco for more comprehensive analysis with tree inventory data.

5 Case Study

5.1 Study site

The Campbell Heights Biodiversity Preserve was selected for the case study. Located at the intersection of 184 Street and 32 Avenue in the City of Surrey, the Preserve occupies 82 hectares of parkland with the southern portion falling within the Agricultural Land Reserve (Figure 6). The Preserve is identified as an important ecosystem hub and corridor in the City's Green Infrastructure Network. It has a diversity of ecosystems with many watercourses originating from the site. Sensitive ecosystems, such as wet meadows, forest swamp and riparian forests, are commonly found in the Preserve. It is predominately a natural area that the city aims to conserve and provide the public space with values of nature and biodiversity while allowing certain recreational activities. An assessment of carbon sequestration potential can inform the decision-making process in managing the Preserve[45], whether its combating climate change or enhancing biodiversity and other ecosystem services.

Figure 6. Site layout of Campbell Heights Biodiversity Preserve (Source: City of Surrey Mapping Online System (COSMOS), 2023)

5.2 Methods

Based on available data and the identified tools, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) and InVEST Carbon Model were selected for application in a Surrey-based case study. CBM-CFS3 was used to estimate and project carbon stocks in the forest components of the study site. Although CBM-CFS3 can assess forest disturbances and model carbon stock changes, it involves complex procedures, requiring specific growth curves (can be generated in BC growth and yield models such as TIPSY and VDYP) and is not applicable to non-forest ecosystems. Therefore, this section will only present the results of the InVEST Carbon Model for the same site, as it is well-suited for various ecosystem types and is relatively easy for city staff to use, aligning with the project's objective of identifying user-friendly tools and methods.

The InVEST Carbon Model requires two major data inputs, which are land cover maps and a table of carbon density values in four carbon pools that cover the above and below ground components of ecosystems. Future land cover maps that project land cover changes will be needed to assess the carbon sequestration over time. The carbon density values can be referenced from the literature or other reliable sources while a value of zero can be inputted if there is no available carbon density data.

5.2.1 Land Cover Map

A terrestrial ecosystems mapping exercise was conducted for the Campbell Heights Biodiversity Preserve during an environmental assessment in 2019, while an agricultural site assessment on the southern portion was commissioned in 2016. A land cover map of the Preserve (Geodatabase), resulting from these previous assessments, was obtained from the city for this case study. The land cover of the Preserve was classified into 72 polygons with field-based data, including tree species composition, age and height, as well as crown closure percentage. For simplicity, the polygons were reclassified into broader categories for the InVest model based on ecosystem types. These mainly include forested swamps, coniferous and deciduous forests, wet meadow as well as disturbed lands such as cultivated/old fields (Figure 7).

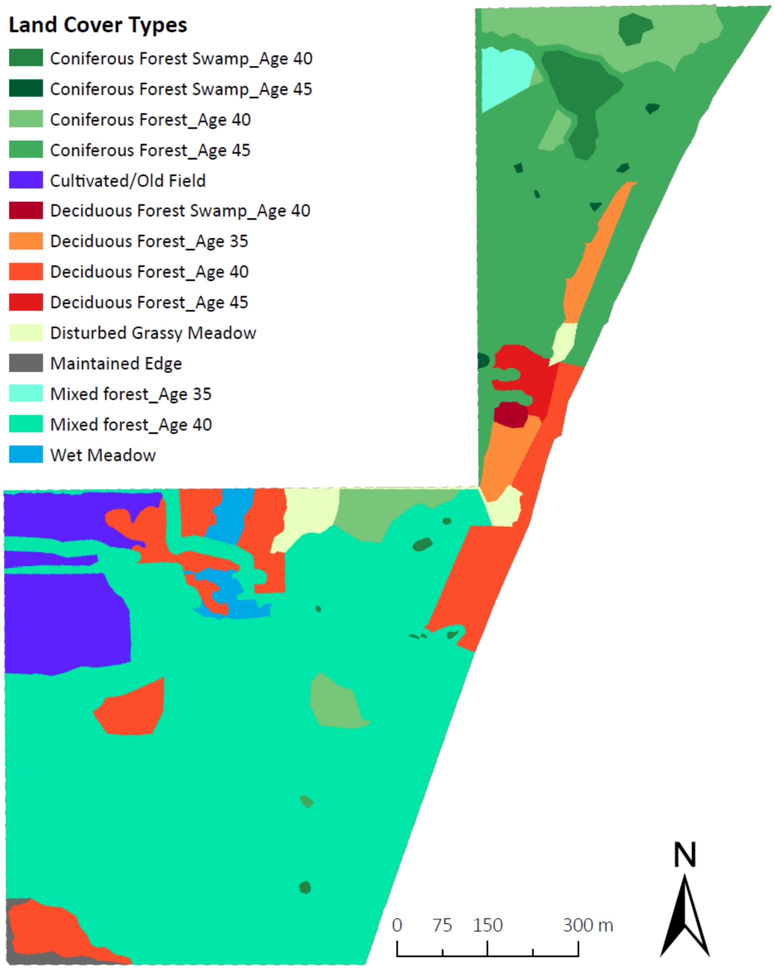


Figure 7. Reclassification of ecosystem types in Campbell Heights Biodiversity Preserve. Age refers to the average forest age in the year of 2019.

Based on the reclassified polygons, land cover maps in the format of a TIFF file, were created for the years of 2019 (the field assessment year), 2030 and 2050. It was assumed that there would not be significant changes in land covers of the Preserve, rather forests would continue to grow, and restoration projects might occur in certain areas of the Preserve. Detailed assumptions are described in the following paragraphs.

5.2.2 Carbon Density Table

The InVEST Carbon Model requires carbon density (tons per hectare) values for aboveground biomass, belowground biomass, soil and dead matter in four pools. The carbon density of forest components was sourced from the FORECAST Model lookup tables (used in generating the regional carbon storage dataset of Metro Vancouver). These lookup tables were calibrated for general south coastal BC forest types, that were age-indexed for both coniferous and deciduous forests. The tree surveying data from the environmental assessment of the Preserve allowed classification of the forest stands into coniferous, broadleaf and mixed types, based on the Standards of Terrestrial Ecosystems Mapping in British Columbia[46] . General assignment of carbon density values for each ecosystem is detailed below (Table 1; please refer to Appendix B for the entire carbon density table).

Table 1. Assignment of carbon density values to specific land covers/ecosystem types in Campbell Heights Biodiversity Preserve

Ecosystem Type	Carbon Density Assignment	Reference
Coniferous Forest Swamp Deciduous Forest Swamp Coniferous Forest Deciduous Forest Mixed forest	-Average stand age was used to assign respective carbon values from the FORECAST Model look up tables - Average values between coniferous and deciduous forests were used for mixed forest stands - Soil carbon pools for forest swamps were replaced by values from reference 2, assuming these soils as mineral soils#.	1) Welham and Seely, 2019[40] 2) Tang et al., 2018[47]
Disturbed Grassy Meadow Cultivated/Old Field Maintained Edge	For simplicity, disturbed grass meadows agricultural fields, maintained forest edge (cleared) were assumed to have stored 75 tons carbon per hectare, an average value of soil organic carbon in BC Farmlands[48]. Only soil carbon is assigned as most of the carbon is stored belowground. Restoration of these ecosystems were assumed to be started in 2024. The following annual carbon sequestration rates were assumed for restoration efforts: Restored grassy meadow: 1.21 tonnes C/ hectare Regenerative Agriculture: 0.3 tonnes C/hectare Mixed forest plantation (on maintained edge): FORECAST Model lookup tables	1) Stanley, 2021[48] 2) IPCC[49]

Ecosystem Type	Carbon Density Assignment	Reference
Wet Meadow	Aboveground biomass carbon (10 tons/hectare) and soil carbon (318 tons/hectare) were assigned, assuming that the ecosystem is dominated by mineral soils# and the stored carbon remains stable over the assessment time.	Tang et al., 2018[44]

Note: # This also includes soils with a top organic layer. However, the sourced data may not adequately reflect soil carbon density, especially in areas with peat formation or very thick organic matter. Generally, it provides relatively conservative estimates.

5.3 Results and Discussion

The InVEST Carbon Model provides results as total carbon per pixel on the current and future land cover maps (TIFF files). Estimates of the total amount of carbon stored in every carbon pool, the changes between current and future land covers are also provided. In this case study, a pixel size of 1x1 m was used in creating the land cover maps. Therefore, the model estimates in those TIFF files can be read as tons of carbon per square meter.

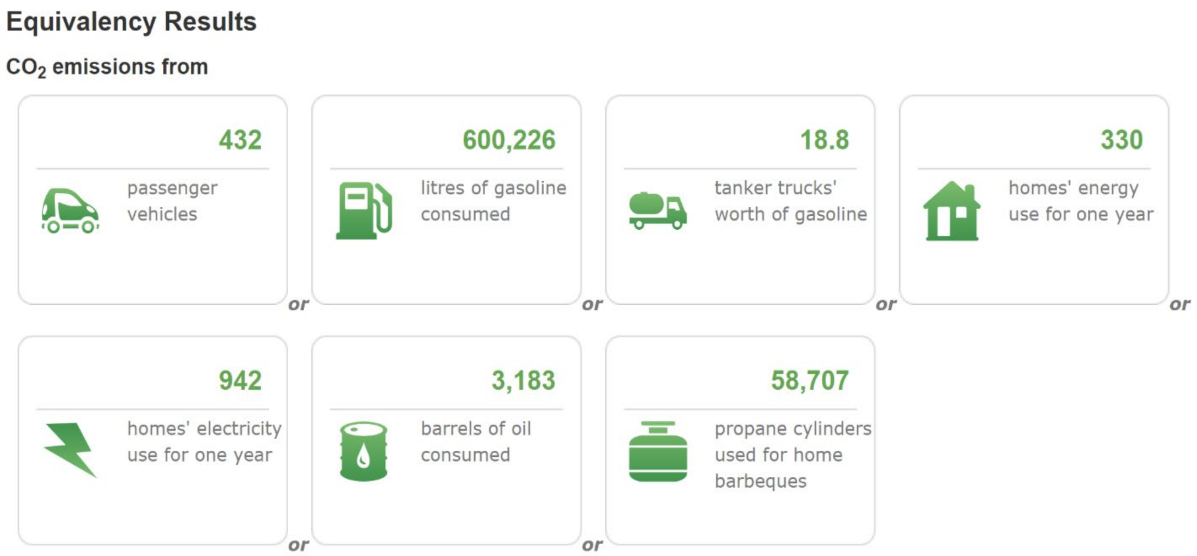
Using the zonal statistics tools in ArcGIS, the amount of carbon sequestered and stored can be calculated for the whole Preserve and individual ecosystem types. The estimates of total carbon stored and sequestered by the Preserve are shown below with the equivalent amount of carbon dioxide.

Table 2. Estimates of carbon sequestration and storage in Campbell Heights Biodiversity Preserve using the InVEST Carbon Model

Estimation Year	Total Amount of Carbon Stored (Tons)		Annual Carbon Sequestration Rate (Tons/Hectare/Year) (Use 2019 as the base year)	
	Carbon	CO_2e	Carbon	CO_2e
2019	23699.85	86978.45	N/A	N/A
2030	28109.68	103162.53	4.98	18.28
2050	35074.77	128724.41	4.55	16.70

Note: CO_2e (carbon dioxide equivalent) is calculated by multiplying the total amount of carbon by the conversion factor 3.67

The Greenhouse Gas Equivalencies Calculator of Natural Resources Canada[50], can be used to translate the model estimates into more concrete terms, such as the equivalent carbon dioxide emissions from vehicles and households (Figure 8).



Equivalency Results

CO_2 emissions from

432 passenger vehicles

or

600,226 litres of gasoline consumed

or

18.8 tanker trucks' worth of gasoline

or

330 homes' energy use for one year

or

942 homes' electricity use for one year

or

3,183 barrels of oil consumed

or

58,707 propane cylinders used for home barbeques

Figure 8. Estimated annual carbon sequestration rate of Campbell Heights Biodiversity Preserve expressed in terms of equivalent co_2 emissions vehicles and households (Source: results of Greenhouse Gas Equivalencies Calculator, Natural Resources Canada)

The resultant land cover maps (TIFF files) generated by the model can also be easily edited in GIS software to facilitate spatial representation of the carbon sequestration potential within the Preserve (Figure 9). By comparing the temporal and spatial distributions on the maps, one can easily identify areas with varying carbon sequestration potential. For example, forested swamps emerge as the ecosystem with the highest potential. This information is valuable for decision-making in land management processes, particularly when changes in land cover are involved.

Overall, the estimates from the InVEST Carbon Model align with our current understanding of carbon sequestration potential across various ecosystems. While the accuracy of these estimates may require field validation, they provide a reasonable trend over time. With the presence of young forest communities, the Preserve is expected to continue sequestering and storing carbon over the next 30 years. A slight decrease in the carbon sequestration rate by 2050 is also reasonable as the forests age. Additionally, the spatial distribution of stored carbon is effective in identifying significant carbon sinks, which can greatly facilitate park planning and management.

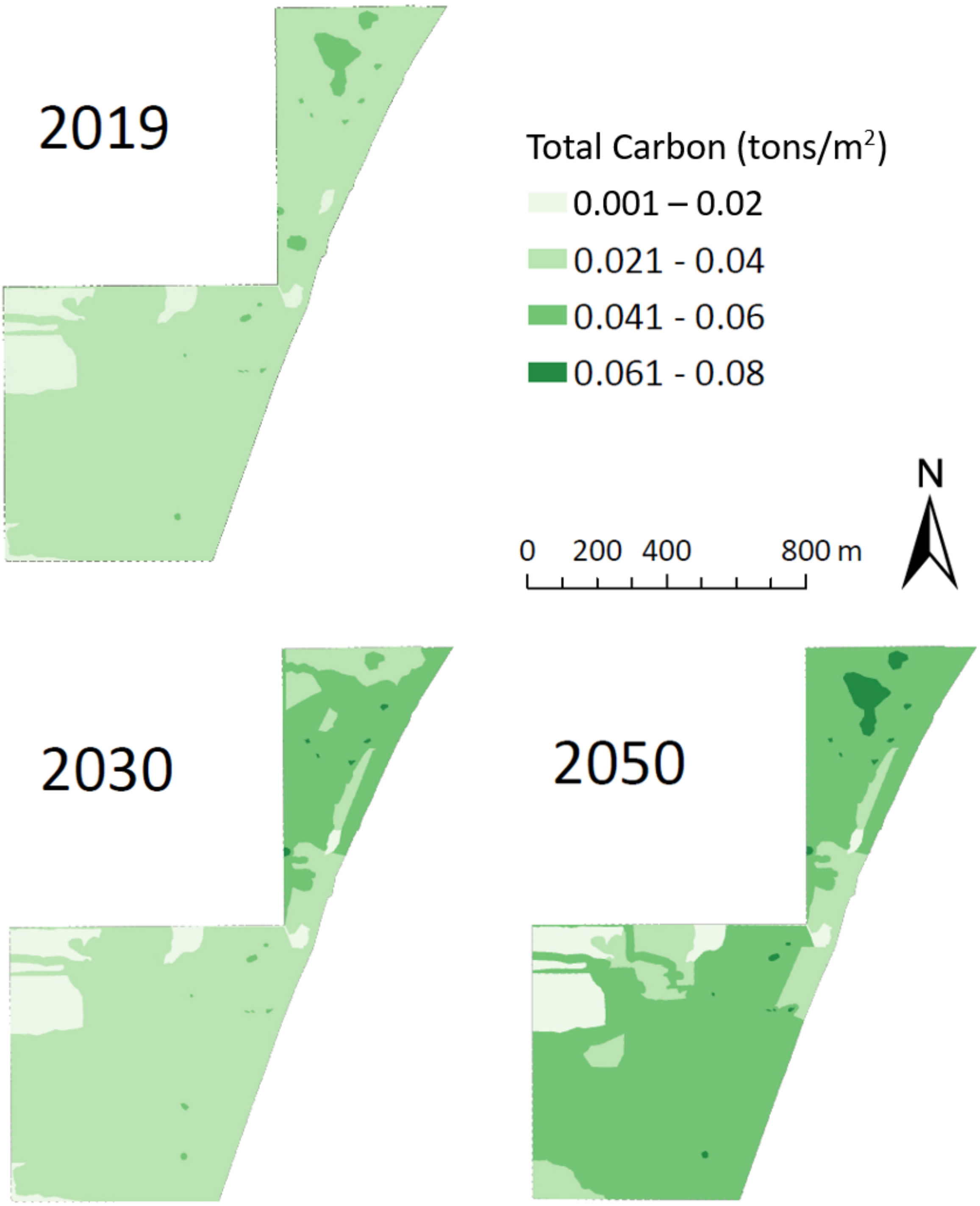


Figure 9. InVEST Carbon Model estimates of total amount of carbon stored in Campbell Heights Biodiversity Preserve for the years of 2019, 2030 and 2050 respectively

5.4 Strengths and Limitations

The InVEST Carbon Model, together with other ecosystem services models in the package, are open source and free to the public. It is easy to use and can potentially be applied to the entire city with suitable sources of carbon density values. It can also be used for carbon valuation by applying a discount rate, which is useful when monetary value of carbon is needed. While preparing land cover maps and finding suitable carbon density values may sometimes be challenging, the model generally offers a methodology that can easily be adapted by city staff in assessing carbon sequestration potential across various ecosystems, especially when there are changes in land covers. However, it also comes with several limitations.

The model assumes a constant rate of change in carbon sequestration for ecosystems, which may differ significantly from real-world conditions. Applying an average carbon density to an entire land cover type overlooks variations within the ecosystem. Additionally, the effects of temperature, precipitation, and both human and natural disturbances cannot be assessed with the same precision as in a process-based model. Carbon sequestration rates are estimated based on the difference between two static carbon values, which may not capture dynamic changes accurately. The model results are largely dependent on the user-defined carbon density values, which may not adequately represent site specific characteristics.

6 Conclusion and Recommendations

There are various tools and methods available for assessing the carbon sequestration potential of ecosystems, many of which are freely accessible and supported by academic research. Before selecting a suitable tool, it is important to define the assessment objectives and scope. No single tool is perfect for all ecosystems. Very often, a balance must be made between practicality and the comprehensiveness of the assessment.

Among the identified tools and methods, the InVEST carbon model is user-friendly and effective for general estimations. While it may not match the accuracy of more complex models, it provides reasonable estimates that can be valuable for decision-making. Application of complex models, such as the CBM-CFS3, is also possible for in-depth analysis, especially with the support of other simpler models developed by the BC government. However, it requires more expertise and resources to operate these complex models.

Regardless of the tools and methods used, field-based data are indispensable as they significantly improve estimations. It is recommended that the city conduct field measurements whenever possible to develop more accurate land cover databases. This is particularly important for sensitive and often overlooked ecosystems such as forested swamps where the soil can store large amounts of carbon. Accumulating field-based data will provide the city with the flexibility to use a greater range of tools and even develop methods tailored to their unique natural assets. In many cases, field measurements are also needed for effective implementation of other strategic objectives, such as enhancing biodiversity and preventing coastal flooding. This provides an opportunity to incorporate carbon sequestration and assessment modeling into broader sustainability goals.

Moreover, the acquisition of remotely sensed data is becoming increasingly common for cities. Fully utilizing these readily available data can complement field measurements, particularly for large-scale assessments. As researchers continue to develop various approaches for delineating natural assets and deriving the properties of above-ground biomass from remotely sensed data, these advancements are expected to further enhance the accuracy and scope of carbon sequestration assessments.

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8 Appendices

8.1 Appendix A – Common Tools for Assessing Carbon Sequestration Potential

Please refer to the next page

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
Blue Carbon Calculator (spreadsheet) Executive Office of Energy and Environmental Affairs, Division of Ecological Restoration Commonwealth of Massachusetts Website: https://www.mass.gov/info-details/use-the-blue-carbon-calculator	➢ Land area (acres) subject to wetland destruction and restoration	➢ Very easy to use in a well-organized spreadsheet ➢ Covers both inland and coastal wetland ecosystems ➢ Can potentially be used for wetland creation projects ➢ Emission rates of both carbon and methane are included ➢ Considers both organic and mineral soils ➢ Using a lookup table with emissions factor sourced from IPCC and literature review	➢ Only applicable to wetland restoration projects ➢ Developed with a focus on wetlands in the northeastern U.S. ➢ Updating of the lookup table may be needed for best available data ➢ Data gaps exist in the lookup table ➢ May not be applicable to projects involve change in wetland types	➢ Restoration of disturbed wetlands ➢ Rewetting of drained wetlands

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
Carbon Budget Model- Canadian Forest Sector [CBM-CFS3 (aspatial) / GCBM (spatial)] Canadian Forest Service Website: https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107	➢ Tree species ➢ Growth curves ➢ Site history ➢ Stand area ➢ Management actions	➢ Applicable to stand and landscape scale ➢ Best available science; Used internationally and regularly updated ➢ Simulates dynamics of all forest carbon stocks ➢ complied with IPCC guidelines (highest level of details) ➢ Modifiable model parameters to suit specific interests ➢ Can include effects of forests management and disturbance ➢ Stand-level Project Creator is easy to use	➢ Intensive user data input ➢ Python scripting knowledge needed for GCBM ➢ Based on natural forests research ➢ Minimum stand size of 0.002 ha ➢ Not suitable for widely spaced trees, shrublands and uneven-aged stands ➢ Excludes harvested woods ➢ Interaction between trees not included ➢ Peat soil dynamics may be included in the future	➢ Natural forests or remnant patches ➢ Detailed forest inventory available ➢ Comprehensive modeling ➢ Analysis of impacts of disturbances

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
Forest Vegetation Simulator (FVS) – Fire and Fuels Extension USDA Forest Service and cooperators Website: https://www.fs.usda.gov/fvs/	➢ Site conditions (e.g., Slope, Elevation and Site Index) ➢ Tree species and DBH (for existing stands)	➢ Individual tree to regional scales ➢ Excellent user support and regularly updated ➢ Based on comprehensive research and development ➢ Multiple variants to cater regional differences; A specific variant for BC (FVS-BC) ➢ Can be applied to uneven-aged and mixed species stands ➢ Can include effects of forests management and disturbance	➢ Primarily designed for natural forests management ➢ Carbon accounting based on a fuel modelling approach ➢ Live fuels (herbaceous plants and shrubs) are poorly represented ➢ Fuel data may be needed for better estimation ➢ Soil carbon pools are not included ➢ The Keyword System (for inputting data and simulations) may require considerable time to get familiar with	➢ Natural forests ➢ Only aboveground biomass is concerned ➢ Impact of fire disturbance is also interested

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) – Carbon Model Natural Capital Project- Standford University and cooperators Website: https://naturalcapitalproject.stanford.edu/invest/carbon	➢ Land cover and land use map (TIFF) ➢ Four carbon pools (aboveground biomass, belowground biomass, soil, and dead organic matter- At least one pool)	➢ User-friendly interface and regularly updated ➢ Allows comparisons for multiple future scenarios ➢ All major carbon pools are included ➢ Allows evaluation of social values of sequestered and stored carbon ➢ The associated software "MESH" allows output visualization without using proprietary GIS software ➢ Flexibility in data input	➢ Oversimplified carbon cycle ➢ Assumes linear change in carbon sequestration rate (i.e. current vs future) ➢ Biophysical processes are not included ➢ Accuracy depends on map resolution and carbon data provided by user ➢ Assumes fixed carbon storage levels in land use and cover types	➢ Readily available land cover and land use maps ➢ Reliable carbon density values available for interested land cover ➢ Quick and easy display of spatial distribution

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
iTree USDA Forest Service and cooperators Website: https://www.itreetools.org/tools	➢ Tree species ➢ Tree DBH (i-Tree Eco)	➢ Comprehensive databases, regularly updated and used worldwide ➢ User friendly interface that can operate with minimum input data ➢ Shrubs can be included in certain tools ➢ Different software for analysis on different scales (iTree MyTree, iTree Canopy, iTree Design, and iTree Eco)	➢ Default values will be used for models if optional data are not provided. ➢ Soil carbon pools are not considered ➢ Net sequestration depends on rudimentary decomposition estimates ➢ Primarily designed for urban forests in the US	➢ Urban forests ➢ Only aboveground biomass is concerned ➢ Limited data available ➢ Versatile tools for various scales

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
LANDIS-II Forest Landscape Model- Forest Carbon Succession Extension The Government of British Columbia (for the extension) Website: https://www.landis-ii.org/home	➢ Model parameters to define biomass proportions ➢ Climate data ➢ Tree life history parameters (e.g. species, longevity, seed dispersal and shade tolerance) ➢ Site map with assigned ecoregions	➢ Stand to landscape scales ➢ Regularly updated and used worldwide ➢ Simulates change as a function of growth and succession, based on probability distribution ➢ Includes effects of climate change and disturbances ➢ Distance-dependent ➢ Extensive cover of carbon pools in forest ecosystems ➢ Active communities of users and developers for support and model improvement ➢ A library of extensions to assess various ecological processes	➢ The latest LANDIS-II core model will only operate on Windows 10 (x64) or Linux ➢ No graphical user interface ➢ Can be computationally intensive ➢ Complex input requirements ➢ Tree species are tracked as age cohorts rather than individual trees ➢ Can be a steep learning curve, especially in defining model parameters	➢ In-depth analysis to include factors, such as changes in temperature, and interaction between trees. ➢ Detailed inventory data and technical expertise available

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
Table Interpolation Program for Stand Yields (TIPSY) The Government of British Columbia Website: https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/growth-and-yield-modelling/table-interpolation-program-for-stand-yields-tipsy	➢ Tree species ➢ Species composition percent ➢ BEC & Ecozone ➢ Site index ➢ Initial stand density	➢ User-friendly software ➢ Connect with graphic tools in the package ➢ Covering common tree species in BC ➢ Easily obtainable data for input ➢ Estimates generated from a more complex growth and yield model (Tree & Stand Simulator-TASS) ➢ Can be used to generate growth curves for carbon modeling in CBM-CFS3	➢ Primarily developed for timber supply projection ➢ Applicable to managed stands only ➢ Carbon estimates of tree components only ➢ Carbon estimates based on empirical volume-biomass equations ➢ Estimates of soil carbon are not available ➢ Species dynamics not considered	➢ Canadian managed even-aged, single- species stands ➢ Only aboveground is concerned

Tool, Developer and Website	Input (Minimum)	Capabilities / Strengths	Uncertainties / Limitations	Best Scenario
Variable Density Yield Projection (VDYP) The Government of British Columbia Website: https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory/growth-and-yield-modelling/variable-density-yield-projection-vdyp	➢ Tree species ➢ Species composition percent ➢ BEC & Ecozone ➢ Tree Age & Height /site index ➢ Crown closure/ stockable area	➢ User-friendly software (WinVDYP7) ➢ Covering common tree species in BC ➢ Can be used to generate growth curves for carbon modeling in CBM-CFS3 ➢ Allows both volume and basal area-based data input	➢ Primarily developed for timber supply projection ➢ Developed for natural/unmanaged stands ➢ Carbon estimates of tree components only ➢ Carbon estimates based on empirical volume-biomass equations ➢ Estimates of soil carbon are not available ➢ Estimates using crown closure is less accurate than basal area-based data ➢ Species dynamics not considered	➢ Canadian unmanaged forests ➢ Only aboveground is concerned

8.2 Appendix B – Carbon Density Table for InVEST Carbon Model

Lucode	Land_Cover	C_above	C_below	C_soil	C_dead	Year
0	Other	0	0	0	0	N.A.
1	Coniferous Forest_Age 40	161.2	7.5	117.2	7	2019
2	Coniferous Forest Swamp_Age 40	161.2	7.5	309	7	2019
3	Mixed forest_Age 35	138	10.8	121.65	10.05	2019
4	Coniferous Forest_Age 45	194.8	8.3	117	8.3	2019
5	Coniferous Forest Swamp_Age 45	194.8	8.3	309	8.3	2019
6	Deciduous Forest Swamp_Age 40	155.8	16	309	18.2	2019
7	Deciduous Forest_Age 35	148.1	15.9	125.7	14.6	2019
8	Disturbed Grassy Meadow	0	0	75	0	2019
9	Deciduous Forest_Age 45	168.3	16.2	128.5	18.9	2019
10	Deciduous Forest_Age 40	155.8	16	127.2	18.2	2019
11	Cultivated/Old Field	0	0	75	0	2019
12	Wet Meadow	10	0	318	0	2019
13	Mixed forest_Age 40	158.5	11.75	122.2	12.6	2019
14	Maintained Edge	0	0	75	0	2019
15	Regenerative Agriculture_Age 6	0	0	76.8	0	2030
16	Regenerative Agriculture_Age 26	0	0	82.8	0	2050
17	Restored Grassy Meadow_Age 6	0	0	82.3	0	2030
18	Restored Grassy Meadow_Age 26	0	0	106.5	0	2050
19	Mixed Forest Plantation_Age 6	9.75	0.55	127.3	3.95	2030
20	Mixed Forest Plantation_Age 26	99.9	9	121.25	6.75	2050
21	Coniferous Forest_Age 56	272.1	11.3	116.8	14.4	2030
22	Coniferous Forest_Age 76	399.4	14.7	118.2	21.2	2050
23	Coniferous Forest Swamp_Age 56	272.1	11.3	309	14.4	2030
24	Coniferous Forest Swamp_Age 76	399.4	14.7	309	21.2	2050
25	Mixed forest_Age 46	186.4	12.45	122.8	13.85	2030
26	Mixed forest_Age 66	267.5	14.15	124.25	20	2050
27	Coniferous Forest_Age 51	235.5	10.5	116.8	13.3	2030
28	Coniferous Forest_Age 71	366.7	14.6	117.7	21.3	2050
29	Coniferous Forest Swamp_Age 51	235.5	10.5	309	13.3	2030
30	Coniferous Forest Swamp_Age 71	366.7	14.6	309	21.3	2050
31	Deciduous Forest Swamp_Age 51	181.5	15.5	309	18.3	2030
32	Deciduous Forest Swamp_Age 71	201	15.1	309	28.2	2050

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33	Deciduous Forest_Age 46	170.6	16.1	128.7	19	2030
34	Deciduous Forest_Age 66	199.6	14.4	131.2	19.9	2050
35	Deciduous Forest_Age 56	186.3	15.6	130.6	21.3	2030
36	Deciduous Forest_Age 76	202.4	15.8	130.9	37.9	2050
37	Deciduous Forest_Age 51	181.5	15.5	129.8	18.3	2030
38	Deciduous Forest_Age 71	201	15.1	131.1	28.2	2050
39	Mixed forest_Age 51	208.5	13	123.3	15.8	2030
40	Mixed forest_Age 71	283.85	14.85	124.4	24.75	2050

Note: Lucode refers to a unique number that allows the model to match carbon density values to a specific area in the land cover map. “0” values are included for areas not defined by the user so that the model can run properly.