EVALUATING THE SOCIOECONOMIC AND ECOLOGICAL VALUE OF CARBON SEQUESTRATION OF THE UPPER CLEARWATER VALLEY FORESTS IN BRITISH COLUMBIA

by

GIANNA CRISTHINA FLOREZ ARIZA

Graduate Certificate in Environmental Impact Assessment, Universidad Jorge Tadeo Lozano, 2019

BSc in Biology, Universidad Nacional de Colombia, 2014

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCES

in the Department of Environmental Science

Thesis examining committee:

Courtney Mason (PhD), Professor and Thesis Supervisor, Departments of Tourism Management / Natural Resource Science

Thomas Pypker (PhD), Professor and Committee Member, Department of Natural Resource Science

Joel Wood (PhD), Associate Professor and Committee Member, Department of Economics

Bianca Eskelson (PhD), Professor and External Committee Member, University of British Columbia Faculty of Forestry

December 2025

Thompson Rivers University

ABSTRACT

Understanding carbon stocks and their sequestration capacity is crucial for effective climate change mitigation strategies that respect ecological integrity and community values. Therefore, identifying landscapes where carbon stocks can be increased through conservation and ecosystem-based management actions is essential. To guarantee long-term permanence of carbon stocks, the support from local communities and stakeholders is necessary.

This research focuses on the carbon sequestration potential of live trees in privately protected forest fragments within the mixed-use landscape of the Upper Clearwater Valley in British Columbia. The valley provides a crucial buffer zone to Wells Gray Provincial Park which can extend forest carbon stocks and mitigate the local impacts of climate change. A mixed-methods approach was used, combining field and LiDAR data with a Random Forest classifier to model forest structure and species composition effectively. Alongside the biophysical analysis, an economic valuation was carried out using the Social Cost of Carbon and carbon market prices. A qualitative assessment of regional stakeholder perceptions was conducted through semi-structured interviews to understand the social value of carbon.

The results reveal that the study area boasts a carbon density of 165.48 Mg C/ha. The forest annually sequesters 0.47 Mt C. This demonstrates strong local capacity for emissions mitigation. This was achieved through modelling carbon at a spatial scale lower than the usual 250 m grid of national-scale models. Considering these attributes and the fact that the valley is part of a vital ecological reservoir within the high-carbon-density Interior Cedar-Hemlock (ICH) zone, it is crucial to maintain and expand forest patches on crown and private lands connected to designated protected areas. This is especially important as climate shifts threaten these subalpine ecosystems.

Stakeholder analysis indicates a strong community commitment to environmental stewardship. Residents viewed forest conservation as indispensable for climate adaptation and also supported local economic pursuits such as tourism. The effectiveness of conservation initiatives depends on landowners, local decision-makers and industry managers to form a joint strategy to maintain a forest corridor across the valley, where economic incentives become a key factor. The land-use arrangement of privately protected areas in the Upper Clearwater Valley can be ideal for an aggregated forest carbon offset project in which privately protected forests expand along the valley's length. A broader protected forest setting could improve the feasibility of generating carbon credits, which would increase both forest carbon, ecological and economic value. The economic value of carbon sequestration in the region is substantial, particularly if it can be integrated into compliance or voluntary markets and provide substantial benefits to landowners to enhance conservation efforts and vegetation management.

This research highlights the importance of privately protected forests as valuable carbon reservoirs. The findings provide a scientifically grounded and socially informed blueprint to leverage private land conservation to enhance ecological connectivity, build resilience, and explore opportunities in the carbon market. To protect and enhance these forest corridors represents more than local conservation objectives; it is a critical investment in a resilient ecological reservoir that safeguards biodiversity and regulates climate for future generations.

Keywords: Carbon Sequestration Model, Private Land Conservation, Stakeholder Engagement, Forest Carbon Markets, Mixed-wood Species Prediction.

TABLE OF CONTENTS

ACKNOWLEDGMENTS

This research was a collaborative effort made possible by the dedication of many professionals and volunteers who share a deep interest in understanding the forests of the Upper Clearwater Valley. Much of this work was rooted in the Thompson Rivers University Research Center, and it was enriched by the connection many Kamloops residents have with Wells Gray Provincial Park. This thesis research was generously supported by Braiding Knowledge Canada, the Blair Climate Change Research Initiative Fund and SSHRC.

First and foremost, I would like to thank my thesis supervisor, Dr. Courtney Mason. His deep appreciation for the park was contagious and opened a window for me to begin discovering this forest from the very start of my journey in Canada. It was through his guidance that I came to realize how this forest made me feel at home—despite being far from home.

The private forests of the region would not have felt so familiar without the generous contributions of Trevor Goward and Curtis Bjork, knowledgeable lichenologist and botanist. I am grateful for their teachings on the natural history of the area, and their help in identifying trees and trails within the study site. I also thank them for watching over us during fieldwork and for the engaging conversations that followed long days in the forest. I especially acknowledge Trevor's scientific guidance in shaping my research design, suggesting potential interviewees and reviewing my results.

The development of the species classification model would not have been possible without MSc. Matthew Coghill, who planted the seed of ecological modeling in my mind. He supported me throughout the LiDAR data collection process and played a key role in designing and developing the models. I also wish to acknowledge Dr. John Church, our drone pilot, whose expertise was essential in refining the data collection strategy to meet our tight timeline.

I am deeply thankful to the TRU students and friends who volunteered their time and energy in the field: Carley Dolman, Alejandra Ariza, Paloma de la Vega, Ruben Quast, Paolo Bigit, Ivonne Calderon, Daniela Rodriguez, Calen Wong, Shiraz, Rabeya Shikdar, and Selena Carl. Your companionship and hard work were invaluable. I also thank my lab mates, Andrea Patino and Catalina Valle, whose experience and professionalism were instrumental during the writing process. They shared with me the full spectrum of emotions that come with being an international student in a master's program.

Finally, I extend my heartfelt thanks to my Colombian family, both in Canada and back home, for their unwavering support throughout every stage of this journey. Even from thousands of kilometres away, my mother made every effort to understand the subject of my thesis and follow my progress. And most importantly, to my husband, Daniel: thank you for being part of nearly every field trip, for driving every weekend after work to support the logistics of my project, for learning how to work like a biologist, and for standing by me through every challenge. Your support made all the difference.

Without the contributions of each of these individuals, this project would not have become the reality it is today.

LIST OF FIGURES AND TABLES

Chapter 1. Introduction

THE IMPORTANCE OF CARBON SEQUESTRATION IN THE CONTEXT OF CLIMATE CHANGE

Ecosystem services are the various benefits that we derive from natural resources. Some of these benefits are direct and indirect economic advantages, such as provisioning food, water, shelter, culture, and recreation. Other benefits are taken for granted since they help regulate the natural system we live in and depend on, such as regulating (e.g., climate mitigation and carbon sequestration) and supporting services. Subsequently, ecosystem services influence human well-being by indicating congruent locations, resources, and land cover types that support human socioeconomic needs and ecological spaces (Alessa et al., 2008). Research that estimates the value of ecosystem services has been increasingly considered in policy development, land-use decisions, and conservation planning initiatives (Menzel & Teng, 2010) because it provides a more holistic and accurate measurement of the management of natural resources (Hrkac, 2021).

Due to pressing concerns about the negative impacts of climate change, several nations have ratified different agreements to establish quantifiable goals to reduce greenhouse gas emissions, safeguard biodiversity, and expand protected areas within their territories. Examples of such international agreements include the Paris Agreement (2015) and the Kunming-Montreal Global Biodiversity Framework (2022). Despite this, some countries, including Canada, have failed to achieve their endorsed targets. As a result, scholars and governments have identified carbon sequestration as a strategic ecosystem service to be evaluated and enhanced in the fight against climate change. The reduction of carbon dioxide emissions is fundamental to successfully tackle the climate change implications for economic development and the lifestyles of all humans of (Kulshreshtha et al., 2000).

The global carbon cycle represents the most essential set of processes linking forests and other vegetation with global warming as they act as carbon sinks, and sequester the carbon emissions generated by human activity. Plants store about 80% of the live biomass on Earth, with an estimated pool of 450 Pg carbon (Bar-On et al., 2018). Of those, approximately 70% is stored in aboveground biomass of forest areas (i.e., stems, branches, barks, seeds, flowers, and foliage of live plants) and is one of the most dynamic terrestrial ecosystem carbon reservoirs (Kumar & Mutanga, 2017). There is considerable uncertainty about the magnitude and regional distribution of forest carbon sinks (Stinson et al., 2011) as they vary substantially due to the impacts of fire, logging, storms, and land-use changes, which immediately contribute to atmospheric carbon fluxes.

Understanding Canada's carbon storage is critical to terrestrial ecosystems, which comprise about 9% of the world's protected and disturbed forests (Sothe et al., 2022). In the current climate change crisis, evaluating any forest remnant in a disturbed area matrix is imperative because it can make a difference regarding carbon sequestration and other ecological processes at a landscape scale. Whereas disturbed lands have a lower capacity for carbon sequestration due to their continuous reduction of vegetation coverage (Piao et al., 2009), evidence suggests that adopting nature-based solutions can effectively enhance the carbon sequestration capacity and increase carbon storage in any landscape (Li et al., 2023).

To maximize scientific knowledge, considering unique configurations of land use is crucial to evaluate carbon sequestration in Canadian landscapes. The focus must be on areas with forest patches with potential ecological connectivity near large extensions of the protected forest, to support carbon flux and provide a connected habitat for fauna and flora. According to the International Union for Conservation of Nature (IUCN), “protected areas provide options for humanity in a rapidly changing world. They ensure the continuing flow of ecosystem services, including maintaining water and air quality and the availability of soil nutrients. They act as carbon sinks, sequestering carbon in the plant biomass and the soil” (Cohen-Shacham et al., 2016).

Additionally, carbon sequestration has recently become a traded service in the global carbon market since governments and industries have realized its potential to accomplish the carbon neutrality targets by 2050 implementing forest carbon offset projects (Environment and Climate Change Canada, 2018). The emergence of this market has led to the recognition that socioeconomic dynamics are as important as scientific determination in the ecosystem service valuation methodology. This approach to forest carbon valuation not only encompasses economic and ecological assessments and forecasts, but it also incorporates active participation from local communities in the management of ecosystems.

LITERATURE REVIEW

Forest Carbon Sequestration Assessment in Canada

Under the Paris Agreement, the Government of Canada committed to reducing greenhouse gas emissions by 30% below 2005 levels by 2030. The Emissions Gap Report 2020 by the United Nations Environment Program advised that, according to current policies, Canada is not on track to meet its current emission targets. Given this situation, nature-based climate solutions need to be implemented in Canada’s climate strategy (Cohen-Shacham et al., 2016) through emission reduction policies to increase support for mitigation efforts (Environment and Climate Change Canada, 2019). The promotion of research that focuses on the connection between land use and carbon cycling through the quantitative assessments of landscape carbon-holding capabilities (Boisvenue et al., 2022) can greatly contribute to Canada's carbon neutrality achievements. The implementation of protective, restorative, and sustainable land management practices also lower terrestrial greenhouse gas emissions and improve land carbon storage (Li et al., 2023).

Carbon sequestration potentials have been estimated using carbon models (Drever et al., 2021; Smyth et al., 2020). Even with a well-established forest carbon model, as is the case for Canada (Environment and Climate Change Canada, 2019), governments at different scales do not include these models when planning greenhouse gas reductions (Lamb et al., 2021) or resource planning. Moreover, the implementation of effective nature-based solutions requires (a) robust estimates of current carbon, (b) an assessment of the land's potential and unrealized potential for carbon sequestration, and (c) the integration of carbon estimates and potential into land-management decision schema (Drever et al., 2021; Walker et al., 2022).

While approximately 23% of forests in British Columbia (BC) are made up of old-growth trees, and 3% of forests support very large trees (Price et al., 2021), the carbon sequestration capacity of the province's ecosystems is undervalued. Matsuzaki et al. (2013) found that the Interior Wetbelt of BC, along the western flanks of the Canadian Rockies and northern Columbia Mountains, is an essential northern latitude carbon reservoir. In this area, there have been vastly underappreciated carbon stocks with the capacity to sequester and store even more carbon for long periods due to the potential of old-growth forests to act as refugia, especially within inland temperate rainforests (DellaSala et al., 2022).

Given the importance of BC forests for the country and the province, the Provincial Government has taken some actions to integrate the carbon storage capacity of natural areas into climate change policies, such as the commitment to implement the 14 recommendations from the Old Growth Strategic Review, which the Government released in April 2020 (Gorley & Merkel, 2020). However, BC has not fully implemented any of these recommendations. Price et al. (2021) found there was a lack of adequate on-the-ground C monitoring, verification of methods, and sufficient data on the forests in the Interior Wetbelt of BC, leading to potential under-reporting of the carbon impacts of industrial logging. These findings raised serious questions about the reliability of carbon emissions reporting and claims about BC's forests being sustainably managed since 2022 (DellaSala et al., 2022).

The failure to properly manage forests, leading to increased carbon stocks, could result in carbon loss, which would significantly impact the atmosphere. To put in perspective the contribution of natural areas to carbon storage and sequestration, Kulshreshtha et al. (2000) estimated that the carbon stored in national parks was about 23 times the 2000 level of Canada's annual emissions (190 Mt C/year). The need to accurately quantify and map carbon stocks emerges as an imperative for managing all of BC's forests. Recent comparisons of field plot measurements or mapped-based estimates of carbon stocks have demonstrated severe undervaluation of old-growth forests (DellaSala et al., 2022).

Due to the lack of complete integration of forest-management policies into climate change mitigation strategies, a particular focus has emerged to maximize forest sinks in all settings and land uses. This includes directly human-managed rural private lands, which can perform as nature-based solutions to climate change. While major forested biomes like the boreal rainforest have the most substantial capacity to affect the global climate, the land sector (e.g., forestry, agriculture, human settlements) is an important part of the natural carbon cycle and the greenhouse gas emissions and removals associated with human management (Steenberg et al., 2023).

Land use changes are key for climate change effects mitigation and to gain improvements in carbon storage and sequestration above and below ground. Carbon-directed land management can also generate secondary effects related to changes in albedo, the substitution of biomass for fossil fuel energy, habitat improvement for wildlife, and watershed protection (Andrews-Key & Nelson, 2025; Sothe et al., 2022; Tolunay & Başsüllü, 2015). There are various directions to implement nature-based land use changes. The first direction is to change the management practices and conservation advocacy, which yield results in the short to medium term (10–30 years). The second is to avoid conversion through activities that increase carbon sequestration. As forests grow, they have more fulsome impacts over the long term (Drever et al., 2021).

Previous studies estimate that full implementation of all cost-effective nature-based climate solutions. These include how avoided conversion and restoration of natural lands and improved management of working lands can provide up to one-third of the global mitigation needed in 2030 to keep warming below 2°C (Drever et al., 2021). This estimate can vary substantially in terms of the mitigation potential due to the specific geography, landscape configuration, the type of action, and local socioeconomic dynamics. To maintain or increase forest carbon on these lands through nature-based pathways is critical for success since their results are usually seen over 30 years. That is why the estimates of carbon sequestration rates are essential for land managers seeking to maximize carbon storage on the landscape and/or in harvested wood products (Chisholm & Gray, 2024).

The Economic Value of Carbon Sequestration

All natural areas and ecosystem services are a type of natural capital. This means they all have an economic value since society obtains economic benefits from resource extraction. Despite their importance, governments often do not consider ecosystems as assets (Kulshreshtha et al., 2000). As the threat of climate change continues to increase, there is a growing need to include natural capital and ecosystem services in the discussions of policymakers about global resource management and sustainable development strategies (Hrkac, 2021).

Trade-offs are a core component of global resource management and using natural capital to create other forms of capital may be considered sustainable as it does not compromise the ability to meet the needs of future generations (Arrow et al., 2012). To achieve future sustainable resource management depends partly on navigating the trade-offs between different ecosystem services through academic research in this area (Cavender-Bares et al., 2015). Costanza et al. (2017) found that the methods and practical applications in valuing ecosystem services were inconsistent and required a more unified and integrated methodology to serve as a tool for public policy-making.

That is why scholars and government institutions have been working on different methods to value carbon sequestration, as it can provide valuable information for policymakers to accomplish the targeted objectives with the least net economic and social cost (Verma & Ghosh, 2024). Monetary valuation offers a formalized framework to assess the economic benefits of ecosystems in a tangible metric for decision-makers. Some researchers believe that assigning monetary values to ecosystems can effectively highlight the importance of preserved and well-managed environments, especially when compared to over-exploited ones (Kermagoret & Dupras, 2018). By emphasizing these economic benefits, we can enhance the ecological importance of natural areas and use this information as a tool in land use planning (Mengist et al., 2023).

One of the most straightforward methods to estimate the scale of the potential benefit of carbon sequestration involves modelling the social damage cost of carbon. This approach tries to account for all damage resulting from carbon emissions, regardless of what sector they impact, because the price for a ton of carbon emissions or sequestration is constant nationally (Nordhaus, 2014). Banasiak et al. (2015) used the social cost of carbon to estimate that the value of carbon sequestered in the United States National Parks is 707.86 USD million annually. Consequently, the 17.5 million metric tonnes of carbon dioxide sequestered per year in National Parks units is equivalent to saving the emissions from the combustion of 2 billion gallons of gasoline per year from being released into the air.

For protected areas in Canada, Kulshreshtha et al. (2000) calculated the replacement cost and the substitute cost method to value carbon sequestration at a large scale (Kulshreshtha et al., 2000). The first one would estimate the value of natural forest carbon based on the cost of replacing projects such as afforestation, reduced deforestation and sustainable land management (King & Mazzotta, 2023). The substitute cost method estimates carbon sequestration values by converting the marginal agricultural lands into forests through afforestation. The cost of carbon determined using the replacement cost with reforestation was $16.25 per tonne; while for the substitution, the cost was $17.50 per tonne.

The economic valuation of forest carbon has extended beyond protected areas to either crown lands or private lands, to maximize the co-benefits of carbon sequestration improvement in all human and natural dimensions. In this sense, the carbon market has played a vital role in achieving lower-scale climate change mitigation goals while providing profitable nature-based solutions through forest carbon offset projects (Dye et al., 2024). A carbon market refers to the buying and selling of credits representing greenhouse gas (GHG) emissions, reductions, or removals. Organizations or individuals buy tradeable units in a carbon market to meet a GHG emissions limit or objective (Environment and Climate Change Canada, 2018). Because forests naturally have continual carbon exchanges with the atmosphere, forest carbon offset programs have also accounted for these exchanges to achieve carbon and other greenhouse gases (GHG) stability over decades and up to a century into the future (Council of Canadian Academies, 2022, December 6).

Offset projects could be costly regarding time and economic resources once the implementation area has been proven ecologically and socioeconomically feasible. Thus, the value of an offset credit fluctuates over time and is primarily influenced by supply and demand and the availability of offset protocols (Environment and Climate Change Canada, 2018). Additionally, the value of the credits depends on the carbon market chosen to sell them. Offset credits from systems targeted toward the compliance market generally sell at a higher price than those generated by the voluntary market because they can be used to meet regulations for emissions reductions (Baker, 2024).

Many forested areas across BC have been impacted by natural disturbances (e.g. insects, wildfire, etc.) and human disturbances (e.g. forestry, road construction, etc.), causing them to turn from carbon sink to carbon source. Therefore, implementing avoided conversion, restoration of natural lands, and/or improved management of lands in the framework of an offset project will allow these areas to return to being a carbon sink faster than natural forest regeneration (Ministry of Forests, 2024).

Even though the implementation process of forest carbon offset projects implies several conditions in the economic dimension to be successful, their occurrence in a high-value ecological area is key to getting carbon sequestration enhancement and other ecosystemic and socioeconomic co-benefits. For instance, NatureBank Asset Management Inc. completed a high-level pre-feasibility assessment to estimate carbon offsets resulting from changes in land management to protect land that constitutes an essential habitat area for caribou in BC (Harmony

Foundation, 2023). Considering a scenario with 100% protection of the current forest harvesting land base, offset estimates indicate a potential volume of 103,390 tCO2e equivalent per year, or half of that under a 50% protection scenario, the potential economic opportunities range from $700,000/year to $3.4 million/year.

Stakeholder Engagement in Ecosystem Services Valuation

Even if the economic valuation is successful, some scholars think it is only through the inclusion of social and developmental goals in projects that it is likely to obtain a reliable cost for enhancing carbon storage in managed and unmanaged forests (Hultman et al., 2020). Only through social inclusion, the carbon benefits will ensure sustainable forest management is relevant at all spatial and temporal scales (Chen, 2012). The design of new strategies to manage natural resources to enhance ecosystem services has often been conducted at the expense of local communities, reducing opportunities for rural development, even if conservation has been tailored to the local context by balancing sustainable use (Heinze et al., 2020). Public participation methods in the valuation can help engage multiple interest or stakeholder groups to better understand what is being used and valued locally (Brown et al., 2014; Darvill & Lindo, 2016).

The economic valuation of ecosystem services has been criticized as limited since economic valuations assume that everyone uses and values the same ecosystem services (Klain & Chan, 2012). The importance of ecosystem services varies among different groups of stakeholders due to place attachment, personal values, and socioeconomic context, and these differences are reflected in ecosystem service use. For instance, stakeholder groups with policy links have more potential to influence management decisions than those with direct associations with the land base (Darvill & Lindo, 2016). Additionally, when multiple stakeholder groups are considered in the evaluation, some aspects of the local society relevant to the management plans emerge, such as competing interests that involve financial gains or where stakeholders act and mobilize at local spatial scales (Howe et al., 2014a).

The participation of key stakeholders in analyzing economic valuation results has facilitated the discussion of strategies that integrate ecosystem services value into development planning. During the process, the stakeholders must recognize the importance of the orders of magnitude of costs and benefits associated with sustainable use of ecosystem services (Darvill & Lindo, 2016; Gómez et al., 2023) to avoid conflict among stakeholder groups, which is an essential part of environmental decision-making for land management (Brown et al., 2014). Consultation with different stakeholder groups can pinpoint potential conflicts before they occur or that might arise from poorly directed land-use change decisions (Darvill & Lindo, 2016).

To use carbon storage as a proxy for climate change at a local scale, research must directly compare carbon storage and socio-ecological conditions (Forgues, 2022). There is a need for holistic approaches that consider both the climate mitigation potential (Lindenmayer et al., 2011) and the socio-ecological characteristics that lead decision-making processes. To enhance carbon sequestration and maintain existing carbon stocks involves changes to land and resource use, which affects local community livelihoods and even the future socioeconomic stability of the region. Subsequently, where appropriate, complete and adequate participation of Indigenous and local communities is relevant to policy-making and implementation processes (Secretariat of the Convention on Biological Diversity, 2010).

One way to guarantee the prevalence of carbon sequestration areas is through sustainable forest management practices by local communities and Indigenous Peoples. This approach can provide one of the most cost-effective and high-volume opportunities for climate change mitigation. Additionally, involving the local community in establishing and maintaining forest areas can create a sense of ownership while generating income (Galik et al., 2009). It is vital to recognize the heterogeneity of local communities and the factors that influence their willingness to participate in such programs (Finley & Kittredge, 2006). For example, in California, forest management projects in private properties managed by their owners that increase carbon sequestration can generate credits that can be sold to offset emissions elsewhere in the market (Marland et al., 2017).

A few studies have quantitatively examined factors that influence the interest of local communities in participating in carbon offset programs. In Norway, Håbesland et al. (2016) assessed the extent to which landowners believe forestry can help mitigate climate change, and how these beliefs influenced their interest in participating. In the United States, Thompson & Hansen (2012) used data from a nationwide mail survey of 429 family forest owners to examine whether there was an interest in a forest carbon sequestration project. They found that respondents with a positive attitude toward participation tended to own smaller parcels and actively manage their forests. Miller et al. (2012) conducted a similar study in Michigan, Wisconsin, and Minnesota. They found that landowners were also more likely to participate if they had positive attitudes toward using forests to mitigate climate change and greatly valued their forest's non-market amenities. Because this is such a decisive motivating factor for participation, any carbon program must be marketed from the landowners' perspectives (Håbesland et al., 2016).

To reach the point where local people can be fully involved in carbon sequestration projects through protected areas, private management, or government plans, it is necessary to ensure stakeholders are informed and understand the carbon storage scenarios in the context of climate change mitigation actions. It is imperative to determine the community's perspectives, priorities, and value judgments towards environmental problems, climate change, and the utilization forms of forest resources and their active and passive use values (Tolunay & Başsüllü, 2015). After identifying the value judgments, it becomes feasible to establish a framework for a community-driven initiative to boost carbon sequestration. This framework should entail tailored management strategies that account for the local population's unique political contexts, socioeconomic expectations, and well-being to guarantee future project continuity.

THESIS STATEMENT

This research argues that forest carbon sequestration management in mixed land-use private lands in the southern buffer zone of Wells Gray Provincial Park can play a vital role in climate change mitigation. This is particularly the case when the management is at a local scale, when projects are evaluated through participatory, integrative environmental, and socioeconomic approaches, and they support sustainable development and local livelihoods.

I will address this statement through the following research questions: 1) What is the carbon sequestration capacity of the small privately owned forested lands in the Wells Gray Provincial Park buffer area to contribute to climate change adaptation?; 2) Is carbon sequestration an important ecosystem service for the local community and decision-makers?; and, 3) Is a carbon offset project viable for the Upper Clearwater Valley community in the buffer zone of the Wells Gray Provincial Park?

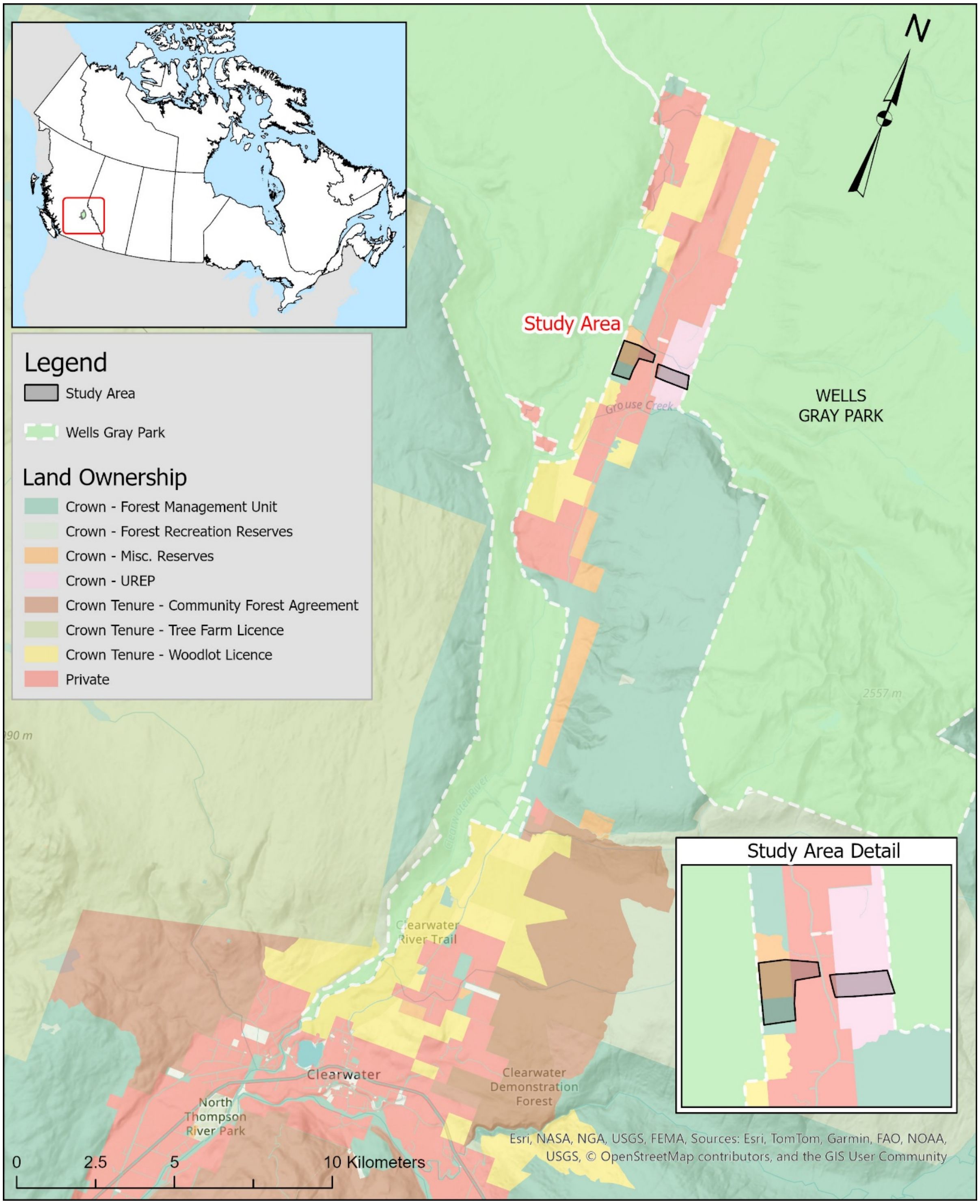
STUDY AREA DESCRIPTION

The study area is in the Upper Clearwater Valley in Wells Gray Country, BC. The region is in a transition zone between the dry Okanagan and the wetter and more variable conditions of the inland rainforest and the higher Cariboo mountains. The climate is cold and temperate. In the Clearwater Valley, the average annual temperature is 3.4 °C. Each year, approximately 1053 mm of precipitation occurs. Here is a difference of 73 mm of precipitation between the driest and wettest months. Throughout the year, there is a fluctuation in average temperatures by 26.0 °C (Climate Data).

The Upper Clearwater Valley, spanning 1000 km², lies adjacent to the southern boundary of Wells Gray Provincial Park, which was established in 1939. The park has undergone several expansions, including the Clearwater River Corridor Addition (3100 ha) and the Trophy Mountain Addition (6934 ha) in April 1996, which both aimed to enhance wildlife habitats (BC Parks, 2025). These additions were the only changes that have been made to the southern border of the park since its establishment. A collaboration between the BC Ministry of Forests and Upper Clearwater residents has resulted in the allocation of approximately 500 ha of crown land for research and educational purposes by Thompson Rivers University.

Edgewood Blue, a private property with educational and research purposes of 10 acres is located east of the university research center (Goward, 2024). Lastly, between the eastern lobe of the Wells Gray Provincial Park and Edgewood Blue, 140 acres of protected forest is managed by The Land Conservancy of British Columbia (The Land Conservancy, 2016).

Even though some private landowners of the valley advocate for increasing the ecological connectivity of the habitat provided by the provincial park, this represents only 5% of the private land in the valley. The spatial distribution of the land in the valley is unique and could potentially provide a larger forested area to enhance ecosystem services. Approximately 9% of the land is privately owned, 31% is crown land used for recreation or categorized as a reserve, and 59% is crown land for timber extraction purposes, as presented in Figure 1.1.



Esri, NASA, NGA, USGS, FEMA, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 1.1. Map showing the land use distribution in the Upper Clearwater Valley, BC.

This research aims to estimate the maximum carbon sequestration potential of forested areas in the valley. The study area of 1.26 km² was chosen based on the criteria of private lands with significant protection, leading to a secondary successional forest with minimal management, at an elevation of 750-800 m. The western area covers a polygon of 0.81 km^2 within the Land Conservancy of British Columbia and Edgewood Blue property. The eastern area of 0.44 km^2 is located in the Thompson Rivers University lands. It includes only one biogeoclimatic zone: Interior Cedar Hemlock subzone dry warm North Thompson. Figure 1.2 displays the study area and the biogeoclimatic zones present in the region.

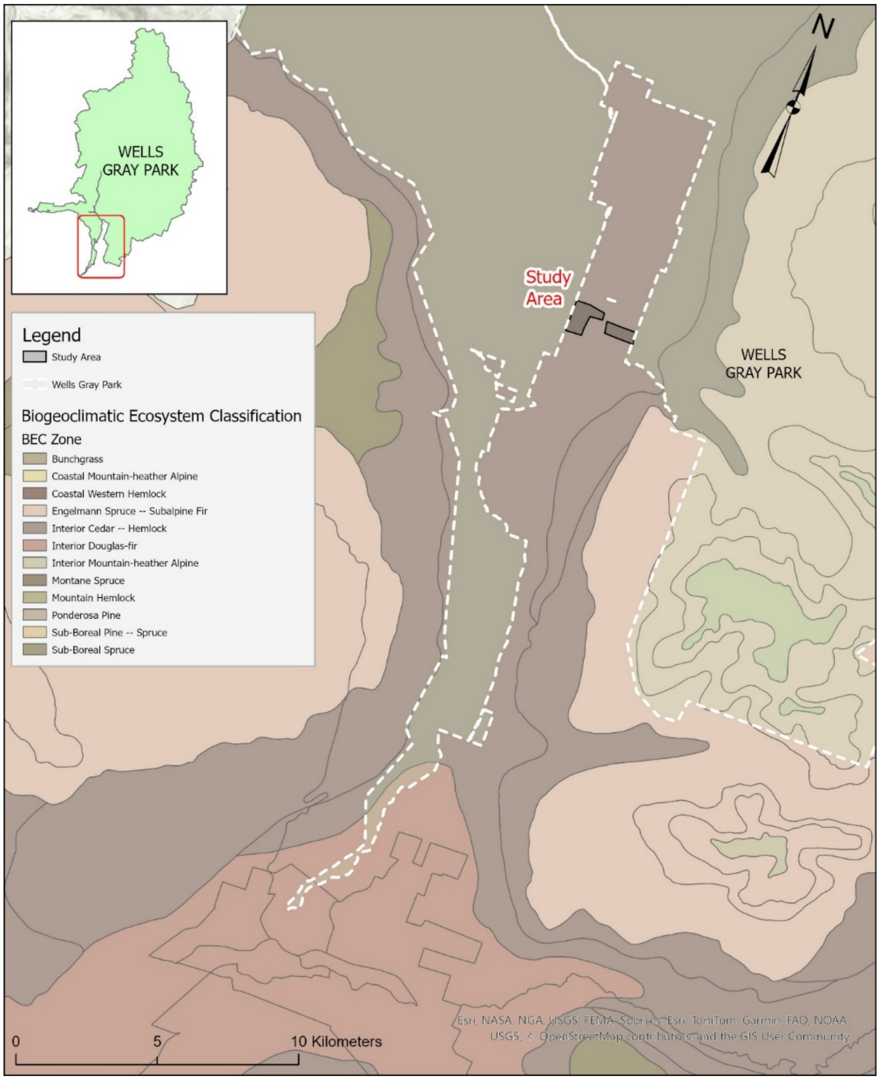


Figure 1.2. Map showing the BEC zones in the study area and the Upper Clearwater Valley.

RESEARCH METHODS

This research applied a mixed methods approach that combines quantitative and qualitative analyses to provide a holistic examination of carbon sequestration enhancement in the socioeconomic context of the land managers and local community of the study area. With this methodological approach, I obtained complementarity, development, and expansion of the results from one method with the findings from the other. The research methods for this project can be divided into three parts: 1) forest carbon sequestration estimation, 2) carbon sequestration economic valuation, and 3) carbon sequestration community-based valuation.

Forest Carbon Modelling

This study provides a high-resolution assessment of carbon storage and sequestration potential of live trees within the privately protected forests of the Upper Clearwater Valley. A multi-stage methodology was developed to achieve this. I combined field-based measurements with remote sensing and machine learning to ensure precision. The carbon assessment began with collecting ground forest structure features data, which was used to train and validate a series of models. LiDAR data was collected to scale up the field data and estimate the forest volume. This remote-sensing method made it possible to measure height and crown features of each tree in the study area. To predict each tree's Diameter at Breast Height (DBH), a regression model from LiDAR-derived metrics was developed.

Subsequently, a Random Forest classifier, augmented with topographic variables, was employed for species-level identification. This detailed forest structural and compositional data was then processed using species-specific allometric equations to calculate live tree biomass, and finally, through the peer-reviewed i-Tree Eco software (Nowak & USDA Forest Service’s Northern Research Station, 2021), to estimate carbon storage and sequestration. In the following sections, each stage of the methodology is described in detail.

Field data collection

Ground and LiDAR data were needed to train the species classification and biomass Random Forest models. These ground-based observations were used to train and validate the carbon model by demonstrating how biomass was distributed among different tree species and forest structures within sample plots. Below is a description of how both methods were conducted in the field.

Ground data

Based on the literature, circular plots of 22 m in diameter were set on both sides of the study area to collect the tree measurements. A plot radius of approximately 11 m (which equates to a plot area of about 380 m^2) is usually used in forest inventories because it represents an optimal balance between efficiency and accuracy (Nowak & US Forest Service, 2021; Steenberg et al., 2023; WWF Canada, 2024), particularly for certain types of analysis like remote sensing-based estimates. Twenty-five plots were set in total on both sides of the study area to come to a total of 9,500 m^2 sampled.

To identify the location of the fifty field plots within the previously established GIS boundaries of the study area, a random plot generator for Google Maps was employed (Ascoli & Starn, 2011). While this method ensured a randomized spatial distribution, the exact location of a subset of plots was adjusted during fieldwork. These adjustments were made on-site due to factors such as extreme topographic conditions (e.g., steep cliffs or ravines) or safety and logistical constraints that would have prevented crew access for accurate measurement. It is acknowledged that such adjustments introduce a potential sampling bias, as the final plot locations may underrepresent certain inaccessible or hazardous terrain types. Ground measurements, which served to complement and calibrate the LiDAR data for forest biomass estimation, were collected from these plots, covering approximately 1% of the total study area.

For each tree, the following data variables were collected: tree’s geographic coordinates recorded with a Garmin ETREX 32x GPS; tree species identified through local taxonomic keys; diameter at breast height (DBH) calculated from the measurement of the trunk at breast height diameter at 1.3 m using a diameter tape and later converted to DBH; total height measured through a SUUNTO clinometer using the geometric method; crown height and width using a tape meter. A crew of field biologists were trained under the standards for field measurements set by Nowak et al. (2021) to ensure the consistency of the measurements. The data was recorded in paper forms as transcripts and then was entered manually into the i-Tree Eco software. Due to resource availability constraints, the data collection was conducted in the autumn months of September and October 2024 and May 2025 to ensure that all the trees had developed their foliage completely in both seasons.

Remote-sensing data collection and snag classification

LiDAR data was collected on June 5th, 2025, with an average temperature of 13 °C and 130 mm of precipitation (Climate Data, 2025). An expert and certified pilot flew the Matrice 300RTK with an attached LiDAR remote sensor DJI Zenmuse L2. The drone flew over the preloaded study area map with terrain following enabled to ensure the 80 m above ground level was constant. The following data collection setting ensured as much of the structure as possible was captured: Surveying based on the digital surface model in DJI Terra 4.5.0 (DJI, 2024). . Flight speed 10 m/s. Number of returns 5 to characterize the depth of the canopy and forest. Non-repetitive scanning allows for better structure from each tree using camera and sensor motion (DJI, 2024). The side overlap ratio is 50%, which is used to capture all the sides of the tree. The camera angle -70° to see through the canopy.

LiDAR point clouds were processed using DJI Terra 4.5.0 to classify ground points using the gentle slope default settings. The LiDAR system generated a dense 3D point cloud with an average point density of 916.95 points/m² and vertical accuracy of 4 cm. The data captured vertical and horizontal forest structure, enabling the derivation of canopy height models and structural metrics such as stem density and crown dimensions. By generating a three-dimensional point cloud, LiDAR enabled the extraction of key structural metrics such as canopy height, crown width, and vertical forest complexity using a Canopy Height Model (CHM) within the LidR package in R (Roussel et al., 2020) to determine biomass and carbon storage.

To optimize the species classification model for the trees, it was necessary to isolate live trees for the allometric biomass analysis. Therefore, standing dead trees (snags) were identified and subsequently excluded from the database. For this purpose, the segment_snags() function of the lidR package in R (Roussel et al., 2020) was used for snag identification within LiDAR point clouds. This function allows for the classification or segmentation of snags (standing dead trees) by assigning a “snags” attribute to each point in the point cloud. While this method successfully identified snag locations, it did not provide species identification for these dead individuals. As the project's objective was to model live biomass and carbon sequestration (processes requiring species-specific allometric equations), only reliably classified live trees could be used in the final estimation. Furthermore, the computational demands of processing the exceptionally dense point cloud for a full inventory were considerable. Analyzing snags for species would have required maintaining this high density, which meant a significant increase in processing time without yielding the necessary species data. Consequently, snags were omitted from the biomass calculations, and the analysis focused exclusively on the live tree component of the forest ecosystem.

Biomass and species classification model

DBH linear model

The diameter at breast height (DBH) of 1,339 sampled trees was predicted using a linear model, with height and species as predictor variables. This model provides the essential DBH-to-height relationship required for biomass estimation. The linear approach was selected for its computational efficiency and is a well-documented method for this purpose in the forestry literature (Esfahani et al., 2026).

Species classification model

Once the forest structure was modelled with the highest possible accuracy using the DBH linear model and the canopy height model from the LiDAR data, machine learning was applied to estimate forest biomass using the Random Forest (RF) classifier using the mlr3 package in R (Lang et al., 2019). RF is an ensemble method that builds multiple decision trees on bootstrapped dataset samples and combines their predictions, improving accuracy and reducing the risk of overfitting.

This study used RF to predict each tree's most likely species identity by integrating structural parameters from LiDAR with terrain, hydrological, and solar indices. Since the LiDAR data only estimates the height of the trees, a species-level identification was needed to determine the live trees' special carbon sequestration and storage features. To do so, a training dataset was created by precisely locating the field-identified trees from the ground inventory within the LiDAR-derived forest model, using their recorded GPS coordinates. The model was then trained to correlate these known species identities with their associated LiDAR structural and environmental metrics, enabling it to predict species for the remaining, unlabeled trees across the entire study area. This dataset included species identification, tree counts, stem diameter at breast height (DBH), and tree height measurements.

To achieve higher accuracy of the forest structure model through more precise species identification of the point clouds representing each tree, it was necessary to incorporate terrain, hydrological, and solar attributes that capture habitat suitability for each species and, consequently, their likelihood of occurrence. SAGA GIS software (Conrad et al., 2015) was used to model these physical attributes of the terrain and generate layers for each one in a digital elevation model. These attributes were included in the Random Forest classification model. The model used recursive feature elimination to determine the best set of features (i.e., variables from terrain, hydrological, and solar indices). The description of the terrain analysis attributes considered is in Table 1.3.

Attribute	Description
Aspect	The compass direction that the terrain slope faces, measured in degrees from 0° (true North).
Slope	The rate of maximum change in elevation (steepness) at each cell, calculated in degrees of inclination.
Channel base	A raster layer identifying the fundamental, base-level channel network.
Channel distribution	A raster layer representing the potential or predicted channel network, including intermittent and ephemeral channels.
Convergence Index	A measure of flow convergence and divergence. Negative values indicate convergent areas where flow accumulates (e.g., valleys, channels), and positive values indicate divergent areas where flow disperses (e.g., ridges, hillslopes).
Diurnal Anisotropic Heating	This models the effect of surface geometry (slope and aspect) on the potential for heating, considering the sun's trajectory.
Curvature	The second derivative of the elevation surface, representing the concavity or convexity of the terrain.
Diffuse insolation	The modeled amount of solar radiation received at the surface from the diffuse (scattered) component of the solar beam, typically over a specified period (e.g., one year).
Direct insolation	The modeled amount of solar radiation received directly from the sun, without being scattered, over a specified period.
LS factor	The combined slope length and steepness factor from the Revised Universal Soil Loss Equation (RUSLE). It quantifies the effect of topography on soil erosion potential.
Multiresolution Ridge Top Flatness index.	This index identifies ridge tops and flat upland areas by analyzing the local terrain across multiple scales. High values typically represent flat, high-altitude regions.
Multiresolution Valley Bottom Flatness index.	This index identifies valley bottoms and flat, low-lying areas by analyzing the terrain across multiple scales.

Attribute	Description
Openness negative	A measure of the dominance of concave (valley-like) features. It is calculated as the average of downward-looking angles within a specified radius.
Opennnes positive	A measure of the dominance of convex (ridge-like) features. It is calculated as the average of upward-looking angles within a specified radius.
Relative Slope Position index	This standardizes a cell's position between a defined valley floor and a ridge top. Values range from 0 (valley bottom) to 1 (ridge top), providing a normalized measure of slope position.
Total Catchment Area	This represents the total upslope area draining through each cell. It is a fundamental layer for hydrological modeling, used to define stream networks and calculate wetness indices.
Topographic Position Index (TPI)	This index compares the elevation of a central cell to the mean elevation of a specified neighborhood.
Terrain Ruggedness Index (TRI)	A measure of the total elevation change between a central cell and its immediate neighbors. It quantifies the heterogeneity of the terrain, with high values indicating rough, rugged areas.
Topographic Wetness Index (TWI)	This index models the spatial distribution of soil moisture and saturation. It is a function of the upslope contributing area (TCA) and the local slope.
Valley Depth	The vertical distance from the current land surface down to a calculated, interpolated valley floor line.
Valley curve	Likely refers to the planform curvature or a specific curvature measure calculated for, or characteristic of, valley bottoms.

Table 1.3 Terrain analysis attributes layers used to maximize species-classification model.

To further optimize the model and explicitly guard against overfitting from uninformative predictors, a recursive feature elimination (RFE) procedure was integrated into the workflow. This process iteratively eliminated predictor variables with the lowest importance scores. The model was re-run after each elimination; if the overall model performance declined, the last removed variable was reincorporated. This recursive process continued until an optimal subset of four key predictor variables was identified. These four predictor variables are a threshold chosen because Random Forest models with fewer than four variables are generally less effective for robust classification. This RFE step ensured the final model was both parsimonious and built on the most relevant structural metrics, thereby enhancing its generalizability and predictive accuracy for forest biomass estimation.

To maximize the predictive performance of the Random Forest classifier, a systematic multiparameter tuning process was employed. A grid search was conducted to optimize two key parameters: mtry (the number of variables randomly sampled as candidates at each split) and num.trees (the total number of trees in the forest). While the common default for mtry is the rounded-down square root of the total number of predictors, the search space for this study was expanded to a sequence of integers from 2 up to this square root value. This comprehensive search was performed to empirically determine the optimal setting, as the anticipated high classification complexity—due to the presence of tree species with similar structural profiles—made exploring all intermediate values necessary. Similarly, the num.trees parameter was evaluated at values of 500 (the typical default), 1000, and 2000. Testing these higher values aimed to ensure sufficient model stability and predictive power by increasing the ensemble's complexity to capture the nuanced relationships within the data better (Probst & Boulesteix, 2017).

This grid search was implemented using 8-fold cross-validation on the training dataset. In this process, the training data was partitioned into eight random, equally sized groups (folds). For each of the eight iterations, seven folds were used to train a candidate model, while the remaining fold was held out as a test set to evaluate its performance. This rotation ensured that every portion of the data was used for validation exactly once. The overall performance for each candidate parameter set was calculated as the average of the balanced accuracy scores from all eight folds. The optimal model was selected based on the highest mean cross-validated balanced accuracy, a metric chosen to ensure robust performance across all species classes (Probst & Boulesteix, 2017), including those with fewer samples.

The final multiparameter set identified through this process was then used to train the definitive species classification model on the entire training dataset. The final hyperparameter set identified through this process was then used to train the definitive species classification model on the entire training dataset.

Canopy height model

Since LiDAR data does not directly provide tree canopy height, the treecbh package (Diószegi et al., 2025) in R was used to determine the crown base height of individual trees. The treecbh package provides functions to detect individual tree level Crown Base Height (CBH) using high-resolution LiDAR data. Individual tree segmentation must be conducted prior. The package is meant to be used within the framework of the lidR package. This variable is a crucial biometric parameter for estimating carbon storage and sequestration. Specifically, the vertical extent of the live crown, derived from total tree height and CBH, is directly related to foliar biomass and photosynthetic capacity. By accurately quantifying the crown dimensions required by the carbon sequestration model software, CBH enables differentiation between total woody biomass and the active, photosynthetically functional component of the tree. This distinction is essential for refining biomass compartment models and for more accurately modelling carbon sequestration dynamics, which are driven by live foliage.

Biomass estimation

The assessment of live tree biomass within the study area was conducted utilizing the i-Tree Eco software (v6). Developed by the US Forest Service, this tool quantifies forest structure, ecosystem services, and associated economic values, aiding researchers and resource managers in decision-making. Its application in this study was deemed particularly appropriate for several reasons. While i-Tree Eco’s foundational models and allometric equations are derived primarily from North American species, its framework is designed for international adaptation. Crucially, the software incorporates localized hourly meteorological data, which adjusts growth and decomposition processes to reflect regional climate conditions. For this study, data from a nearby Canadian weather station ensured these calculations were tailored to the local environment. Additionally, the software's methodological focus aligns with the context of this research. i-Tree Eco's core studies emphasize non-mature, suburban, and urban forests, making it a suitable analytical framework for the study area's character. Furthermore, as Canada is a partner country for which the software has been specifically calibrated, its use here is supported by pre-existing regional validations.

i-Tree Eco offers necessary flexibility in data input, capable of processing field measurements from individual trees, complete inventories, or randomized plots. This allowed for the direct integration of this study's field-collected data with local pollution and weather parameters to produce a standardized, quantitative assessment of biomass, structure, and ecosystem services. The input data used to model biomass were obtained from the species classification model, DBH measurements from the linear model, and height measurements from LiDAR data processing.

Biomass for each measured tree was calculated using allometric equations from the literature (Nowak, 2021). Equations that predict above-ground biomass were converted to whole tree biomass based on root-to-shoot ratio of 0.26 (Cairns et al., 1997 in Nowak, 2021). Equations that compute fresh-weight biomass were multiplied by species- or genus-specific conversion factors to yield dry-weight biomass. These conversion factors, derived from average moisture contents of species given in the literature, averaged 0.48 for conifers and 0.56 for hardwoods (USDA 1955; Young and Carpenter 1967; King and Schnell 1972; Wartluft 1977; Stanek and State 1978; Wartluft 1978; Monteith 1979; Clark et al. 1980; Ker 1980; Phillips 1981; Husch et al. 1982; Schlaegel 1984a,b,c,d; Smith 1985 in Nowak, 2021). As deciduous trees drop their leaves annually, only carbon stored in wood biomass was calculated for these trees. Total tree dry-weight biomass was converted to total stored carbon by multiplying by 0.5 (Forest Products Lab, 1952; Chow and Rolfe 1989 in Nowak, 2021).

The multiple equations used for individual species were combined to produce one predictive equation for a wide range of diameters for individual species. The process of combining the individual formulas (with limited diameter ranges) into one, more general species formula, produced results that were typically within 2% of the original estimates for total carbon storage of the urban forest (i.e., the estimates using the multiple equations). Formulas were combined to prevent disjointed sequestration estimates that can occur when calculations switch between individual biomass equations. If no allometric equation could be found for an individual species, the average of the results from equations of the same genus was used. If no genus equations were found, the average of the results from all broadleaf or conifer equations was used (Nowak, 2021).

Carbon storage and sequestration model

The carbon (C) storage values were estimated and converted into carbon sequestration estimates using the i-Tree Eco tool (Nowak, 2021) developed based on UFORE-C: Carbon Storage and Sequestration, which calculates total stored carbon, and gross and net carbon sequestered annually by the urban forest based on field data (Nowak & Crane, 2000). Carbon dioxide (CO2) in the atmosphere is necessary for plants and trees to grow. Trees absorb carbon dioxide during photosynthesis, storing carbon and producing oxygen as a byproduct of photosynthesis. Carbon sequestration is the process of removing carbon from the atmosphere and storing it in a physical element (e.g., a tree). i-Tree Eco estimates carbon storage in trees, annual carbon sequestration, and emission of carbon via tree decomposition. The required inputs from the field and LiDAR data are: tree species (field data), DBH (regression model), total tree height, crown dieback and crown light exposure (LiDAR data). The following description of the equations used from the carbon storage and sequestration model is explicitly written in the UFORE document referenced earlier.

Carbon storage is estimated by multiplying tree biomass by 0.5 (Chow and Rolfe 1989 in Nowak, 2021). To prevent carbon storage overestimation for very large trees, total carbon sequestration is limited to a maximum of 40 kg C / cm DBH growth once a tree reaches 7,500 kg of carbon in i-Tree Eco. To estimate annual gross carbon sequestration, the tree DBH is incrementally increased in the computer model based on an estimated annual growth rate. The carbon storage in the current year (year 0) is then contrasted with carbon storage in the next year (year 1) to estimate the annual sequestration. If a tree's carbon storage is over 7,500 kg and the tree is alive, carbon sequestration for these large trees is estimated based on the sequestration rate (kg/cm DBH growth) when the tree reached 7,500 kg C storage. A maximum sequestration rate was set at 40 kg/cm DBH growth if the tree's storage was greater than 7,500 kg. These sequestration values are added to the storage value annually, so storage can exceed 7500 kg, but the sequestration rates are prevented from growing geometrically based on carbon equations applied to large trees (Nowak, 2021).

The average diameter growth from the appropriate land-use and diameter class was added to the existing tree diameter (year x) to estimate tree diameter in year x+1. For trees in forest stands, average DBH growth was estimated as 0.38 cm/yr (Smith and Shifley 1984 in Nowak, 2021); for trees on land uses with a park-like structure (e.g., parks, cemeteries, golf courses), average DBH. growth was 0.61 cm/yr (deVries 1987 in Nowak, 2021); for more open-grown trees, DBH. Class-specific growth rates were based on Nowak (1994). Average height growth was calculated based on formulas from Fleming (1988) and the specific DBH growth factor used for the tree (Nowak, 2021). As the base growth estimates used are from more northern U.S. areas, a new growth approach was used that utilizes length of growing season to determine the base growth rate.

To determine a base growth rate based on length of growing season, forest growth estimates (Smith and Shifley, 1984) were standardized to growth rates for Minnesota (153 frost-free days) based on: Standardized growth (SG) = measured growth x (153/ number of frost-free days of measurement). Crown light exposure measurements of Growth = SG / 2.26 were used to represent forest growth conditions. Growth rates were adjusted based on tree condition. For trees in fair to excellent condition, base growth rates were multiplied by 1 (no adjustment), poor trees' growth rates were multiplied by 0.76, critical trees by 0.42, and dying trees by 0.15 (dead trees' growth rates = 0). Adjustment factors were based on percent crown dieback and the assumption that less than 25% crown dieback had a limited effect on DBH growth rates. The difference in estimates of C storage between year x and year x+1 is the gross amount of C sequestered annually (Nowak, 2021). Table 1.4 presents the criteria used to estimate species-specific growth rates in the study area.

Common Name	**Species Name**	**Percent Leaf Type**	**Leaf Type**	**Growth Rate**	**Longevity**	**Height at Maturity (feet)**
White spruce	*Picea glauca*	Picea	Evergreen	Slow	Long (55+yrs)	80
Western hemlock	*Tsuga heterophylla*	Pinus	Evergreen	Slow	Long (55+yrs)	170
Western red cedar	*Thuja plicata*	Picea	Evergreen	Slow	Long (55+yrs)	150
Subalpine fir	*Abies lasiocarpa*	Picea	Evergreen	Slow	Long (55+yrs)	90
Lodgepole pine	*Pinus contorta*	Pinus	Evergreen	Fast	Long (55+yrs)	99
Trembling aspen	*Populus tremuloides*	Hardwood	Deciduous	Fast	Moderate (35-55yrs)	65
Black cottonwood	*Populus balsamifera*	Hardwood	Deciduous	Fast	Moderate (35-55yrs)	100
White birch	*Betula papyrifera*	Hardwood	Deciduous	Fast	Moderate (35-55yrs)	70

Table 1.4 Species growth rate criteria to model carbon sequestration. Taken from i-Tree Species Database.

Tree death leads to the eventual release of stored C. In estimating the net amount of C sequestered by the forest, C emissions due to decomposition after tree death must be considered. To calculate the potential release of carbon due to tree death, estimates of annual mortality rates by condition class were derived from a study of tree mortality (Nowak 1986 in Nowak, 2021). Annual mortality was estimated as 1.92 percent for trees 0 to 3 inches in the good-excellent class; 1.46 percent for trees more than 3 inches in the good-excellent class; 3.32 percent for trees in fair condition; 8.86 percent for poor condition; 13.08 percent for critical condition; 50 percent dying trees, and 100 percent for dead trees. Two types of decomposition rates were used: 1) rapid release for above-ground biomass of trees, and 2) delayed release for standing dead trees and tree roots. Dead trees have an increased probability of being measured in the future tree inventories and decomposition rates must reflect this difference. These trees were assumed to decompose over a period of 20 years (Nowak, 2021).

Estimates of C emissions due to decomposition were based on the probability of the tree dying within the next year and the probability of the tree being removed using the formula:

$$Emission = C \times M_c \times \sum p_i((D_{remove}) + (D_{s\tan d}))$$
$$D_{remove} = (p_{ab} / y_i)(1/d_m) + ((1 - p_{ab}) / y_i)(1/d_r)$$
$$D_{s\tan d} = ((y_i - 1) / y_i)(1/d_r)$$

where Emission = individual tree contribution to carbon emissions; C = carbon storage in the next year; Mc = probability of mortality based on condition class; i = decomposition class (based on number of years left standing before removal); pi = proportion of the land use tree population in decomposition class i; pab = proportion of tree biomass above ground; yi = number of years left standing before removal (yi → ∞ for natural decomposition); dm = decomposition rates for above-ground biomass (3 years); and dr = decomposition rate for standing trees and tree roots (20 years) (Nowak, 2021).

Individual tree estimates of mortality probability and decomposition rates were aggregated upward to yield total estimates of decomposition for the tree population. The amount of carbon sequestered due to tree growth was reduced by the amount lost due to tree mortality to estimate the net carbon sequestration rate (Nowak, 2021).

Carbon sequestration model uncertainties

The limitations associated with carbon storage estimates are the same as with tree biomass estimates, as carbon storage is directly related to biomass. Overall, the storage estimates are reasonable, and the standardized values per unit tree cover are comparable to estimates for U.S. forests and from other cities around the world (Nowak et al. 2013a in Nowak, 2021). National estimates of forest carbon storage and sequestration have been estimated through the years using this procedure (Nowak 1993, Nowak and Crane 2002, Nowak et al. 2013a in Nowak, 2021). Estimates of storage could be improved with biomass equations developed for landscape conditions. Capping carbon sequestration after the tree reaches 7,500 kg is also a limitation, however, the cap prevents extremely large estimates from occurring via the logarithmic biomass equations used. Estimates of gross carbon sequestration are dependent upon good biomass and tree growth equations. Growth rates for trees will range between 0 cm DBH/yr (dead trees) to 2.54 cm DBH/yr for fast-growing, open-grown healthy trees in areas with no frost (Nowak & US Forest Service, 2021).

Estimated growth rates are average rates where rates of individual trees may be higher or lower than the estimated class average. These growth rates for “moderate” trees are within range for measured urban and forest tree growth (e.g., deVries 1987, Fleming 1988, Frelich 1992, Nowak 1994b, Smith and Shifley 1984, Wood 2010 in Nowak, 2021). The estimated growth is based on the tree species, condition, and crown light exposure of the measured tree. Better long-term growth rates for trees will help improve growth estimates. Net sequestration is based on gross sequestration minus losses due to decomposition. Decomposition estimates are quite rudimentary and are based on various assumptions of mortality and decomposition rates. Improved research on decomposition rates and mortality rates for urban trees are needed to enhance the net sequestration estimates (Nowak & US Forest Service, 2021).

Economic Valuation

I employed the avoided damage costs approach to estimate the economic benefits of carbon sequestration and storage with a focus on cost-based methods. This method estimates the economic benefit of removing a ton of CO_2 from the atmosphere by calculating the economic damage that ton would have caused if it had remained in the atmosphere. This involved considering three values: the Social Cost of Carbon (SCC) for Canada, the value of a ton of carbon in the North American voluntary market, and the provincial compliance market through the British Columbia Output-Based Pricing System. By comparing these prices, I aimed to establish a societal perspective on carbon valuation that aligns with a market-based approach. The total value of the carbon sequestration potential for each area was converted into monetary value using the following equation:

$$Vc = Q \times P \times S$$

Where

Vc = service value of carbon sequestration,
Q = Net carbon storage (t/ha/yr),
P = carbon prices (CAD/t C),
S = Area of forest or land cover (ha).

SCC estimates the economic cost of an additional ton of carbon dioxide emitted to the atmosphere (Nordhaus, 2014) or the monetized benefit and its present value obtained by sequestering an additional metric ton of carbon from the atmosphere (Sil et al., 2017). For this analysis, I used the SCC set by the Government of Canada for 2025 of $271 per ton of carbon equivalent (Environment and Climate Change Canada, 2023) as the first economic value entry for the i-tree Eco tool model of carbon sequestration.

In addition to the SCC, there are two types of carbon markets: voluntary and compliance. The distinction lies in whether the tradable units serve to meet voluntary commitments or regulatory emissions limits. Individuals or organizations that voluntarily limit GHG emissions can utilize units from the voluntary market, while compliance market units are reserved for companies constrained by government regulations. Nonregulated entities may also purchase from the compliance market to achieve voluntary emissions reduction goals (Environment and Climate Change Canada, 2018).

For this study, I assigned the compliance market's carbon price using the British Columbia Output-Based Pricing System (BC OBPS), which for 2025 is set at CAD95 per tonne of carbon dioxide equivalent (tCO2e) (International Carbon Action Partnership, 2024). This carbon pricing model incentivizes industrial emitters to reduce GHG emissions through a performance-based system and offers flexible compliance options, including BC carbon offset units and credits from approved carbon removal or reduction projects under the Greenhouse Gas Industrial Reporting and Control Act (GGIRCA), verified by accredited bodies (Clean BC, 2025). Notably, carbon offset projects in the forestry, ecosystem conservation, and land use sectors accounted for the largest volume of carbon credits, despite a 66% decline from 2022 levels in 2023 (Forest Trends' Ecosystem Marketplace, 2024).

While the price of voluntary carbon credits in Canada fluctuates widely, average offset prices typically range from approximately $5 to $30 per tonne (Forest Trends' Ecosystem Marketplace, 2024). This variability is influenced by factors such as the type of carbon offset project, the carbon standard under which it was developed, the project location, associated co-benefits, and the vintage year. For this research, I utilized the price of $24 per ton of CO2e, reflecting the average price paid by buyers in 2024

Stakeholder-Based Social Valuation

To effectively evaluate carbon sequestration and its future integration into local programs to adapt to climate change, I sought insights from relevant stakeholders with different connections to the territory in which the study area is located. I conducted interviews to develop lasting local plans for ecosystem service management (Kothari et al., 2013). I valued the perspectives of decision makers and those with scientific expertise, land-use knowledge, and management experience regarding the forest's carbon sequestration potential. This project component followed a framework featuring the following key aspects: (1) early identification of relevant stakeholder representatives, (2) continuous stakeholder participation, and (3) questions tailored to the decision-making context (Gomez et al., 2023).

I carried out semi-structured and conversational interviews with stakeholders, all approved by the Thompson Rivers University Research Ethics for Human Subjects Board. Each interview included 10-15 open-ended questions and prompts (see Appendix A). I adjusted some questions based on each interviewee's background. I gathered in-depth and highly personalized answers using semi-structured interviews, allowing participants to control the information they shared. My questions focused on participants' familiarity with carbon sequestration and their perceptions of its ecological benefits. We also covered the viability of creating a forested corridor along private areas and crown lands to enhance carbon storage and ecological connectivity, the socioeconomic implications of increasing forest areas in the valley, the implementation viability of a forest carbon offset project, and government support for conservation initiatives.

To illustrate this process, a forest carbon project scenario was presented to the interviewees to gather their perspectives on the community's willingness to participate in such a project. This was followed by discussions on the current and future challenges of forests in the valley on both private and crown lands. Moreover, it was essential to understand a priori the structure of the community through key questions like who depends on the forest, has formal or informal authority and might be significantly impacted by changing land management? These questions are crucial to obtain valuable insights about the land, wildlife, forest changes, or traditional management practices.

I identified relevant stakeholders based on previous research conducted by Thompson Rivers University graduate students in the valley (Bogetti, 2024; Patino, 2025). After interviewing four stakeholders, I recruited additional participants using the snowball sampling method (“Snowball Subject Recruitment,” 2017). The participants represented various stakeholder groups, including scientific researchers, BC parks staff, non-profit employees or volunteers, forestry managers, tourism operators, Clearwater District staff, and regional politicians. The details of the interviews are shown in Table 1.5.

Participant	Position	Interview date	Interview mode
Alsid Prime	Director of Corporate Services at Clearwater District	2025-01-22	Virtual
Chance Breckenridge	FireSmart Coordinator at Clearwater District	2025-01-22	Virtual
Danielle Toperczer	Program director at Thompson-Nicola Conservation Collaborative	2025-08-06	Virtual
Stephanie Russell	Conservation Specialist - South Strategic Priorities at BC Parks	2025-01-22	In-person
Randy Sunderman	Economic development consultant and BC Greens member	2025-01-17	In-person
Trevor Goward	Co-curator of Lichens (University of British Columbia) Enlichened Consulting Ltd. Upper Clearwater Valley resident	2025-01-15	In-person
Tom Dickinson	Emeritus Professor of Biology at Thompson Rivers University	2025-01-26	In-person
Nancy Flood	Professor Emerita at TRU President, BC Nature & Kamloops Naturalist Club	2025-05-30	In-person
Roland Neave	Wells Gray Tours Owner Author of Exploring Wells Gray	2025-02-05	In-person
Gy Ovenden	Ecology consultant and Former Wells Gray Provincial Park Guide	2025-02-23	Virtual
Catherine Armstrong	Ex-executive director The Land Conservancy Trust	2025-06-11	Virtual
George Brcko	General Manager of Wells Gray Community Forest Corporation	2025-02-04	Virtual

Table 1.5 List of participants interviewed and their affiliations.

Before conducting the interviews, I invited each participant to sign a consent form outlining the research scope and their rights regarding anonymity and withdrawal; all participants signed the consent form. None of the participants withdrew from this research. I recorded each interview using the Microsoft Teams TRU account or a recorder, transcribed them verbatim, coded the data accordingly, and returned the transcripts to participants for verification. I verified the collected data with individual participants to ensure reliability and accuracy before compiling the research into its final form. I sent raw transcriptions to each participant for review.

I analyzed the qualitative data from the interviews using the thematic analysis method, creating codes for common themes identified and then analyzing them for commonalities and divergent patterns (Elo & Kyngas, 2008). The themes included: the effect of land-use decisions on prioritizing the benefits of carbon sequestration, the biggest challenges for forest conservation, the viability of forest conservation and restoration without a forest carbon offset project, local community willingness to participate in a carbon offset project, the impact of this type of project on economic activities, and government support for forest conservation. I included direct quotes from interviewees in Chapter 3 of this thesis to ensure local voices are represented as often as possible.

RESEARCHER POSITIONALITY

Several factors throughout my career have led me to propose this research and select the approaches to address my research questions. I believe these approaches can be adapted to other locations in the context of climate change with appropriate sociopolitical adjustments.

My interest in landscape ecology began during my undergraduate studies in biology in Colombia, where I examined how local socioeconomic dynamics influence forest conservation, wildlife habitats, and land-use conflicts. My early research highlighted the struggles of landowners in conserving endemic species amid government pressure to expand cattle ranching. Later, through a graduate certificate project, I explored land reclamation strategies to restore mined areas and create wildlife corridors. Professionally, seven years as an environmental consultant in

Colombia’s extractive industries gave me a contrasting perspective on balancing conservation with regional development needs. More recently, my engagement with carbon offset projects in Latin America revealed both their potential to incentivize conservation and the challenges posed by complex certification processes and unresolved land-use conflicts. These experiences further shaped my interest in integrating ecological preservation with socioeconomic realities.

Consequently, I decided to leverage my experience through the use of the scientific and socioeconomic approaches to the evaluation of the criteria for designing a forest carbon offset project. The Upper Clearwater Valley is a region where the local community is eager to engage in ecological connectivity efforts to address local climate change impacts, such as wildfires. Community members are also interested in the management of the forest to create habitats and enhance carbon sequestration. My focus for this research is the decision-making and the long-term continuity of the project through local community engagement. The findings of this study are based solely on the participants' opinions and perspectives, with minimal reference to my own ideas and only include the scientific and objective economic analysis of the creation of a private protected forest in the valley.

OVERVIEW OF THE THESIS

This thesis is divided into three content chapters that cover the approaches chosen to address the importance of carbon sequestration in the Upper Clearwater Valley: the ecological, economic, and social dimensions. The first chapter describes the opinions and perspectives of some of the relevant stakeholders of the area about forest management towards carbon sequestration enhancement. The content addresses some socio-political, economic and land use constraints that can occur when attempting to create private protected areas to form an ecological viable forest corridor.

The second chapter estimates the carbon sequestration capacity of the study area based on the two complementary methods: a tree inventory-based carbon sequestration model and a geospatial model based on remote-sensing data and machine-learning modelling. These results determine the ecological importance of the area to be protected through private management and the magnitude of its contribution to increase carbon sequestration in the specific area. It formulates actions for carbon stocks enhancement in the short and medium term and its considerations at the landscape scale as part of the buffer of the Wells Gray Provincial Park.

The final third chapter evaluates the economic valuation of the study area in light of provincial commitments to achieve carbon neutrality. It examines the coherence of the social cost of carbon in relation to the region, comparing it to the actual price per ton of carbon in both compliance and voluntary carbon markets. Additionally, it assesses the economic viability of the area for participation in a forest carbon offset project from a project management perspective and the strategies that can be taken to maximize the project's ecological value.

REFERENCES

Alessa, L. (Naia), Kliskey, A. (Anaru), & Brown, G. (2008). Social–ecological hotspots mapping: A spatial approach for identifying coupled social–ecological space. *Landscape and Urban Planning*, *85*(1), 27–39. https://doi.org/10.1016/j.landurbplan.2007.09.007

Andrews-Key, S. A., & Nelson, H. (2025). Using climate vulnerability assessments to implement and mainstream adaptation by the forest industry into forest management in Canada. *Frontiers in Forests and Global Change*, *8*, 1434585. https://doi.org/10.3389/ffgc.2025.1434585

Arrow, K., Dasgupta, P., Goulder, L., Mumford, K., & Oleson, K. (2012). Sustainability and the measurement of wealth. *Environment and Development Economics*, *17*(3), 317–353. https://doi.org/10.2307/26265518

Ascoli, A. R., & Starn, R. (2011). I-Tree Eco Tool v6 User's Manual. *California Italian Studies*, *2*(1). https://doi.org/10.5070/c321011568

Baker, M. (2024). *Introduction to Forest Carbon Offsets*. Bluesource, Calgary, Alberta.

Banasiak, A., Bilmes, L., & Loomis, J. B. (2015). Carbon Sequestration in the U.S. National Parks: A Value Beyond Visitation. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2577365

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences*, *115*(25), 6506–6511. https://doi.org/10.1073/pnas.1711842115

BC Parks. (2025). *Wells Gray Park: Trophy Mountain | BC Parks*. BC Parks. https://bcparks.ca/wells-gray-park/trophy-mountain/

Bechtold, W. A., & Patterson, P. L. (2015). *The Enhanced Forest Inventory and Analysis Program � National Sampling Design and Estimation Procedures* (No. SRS-GTR-80; p. SRS-GTR-80). U.S. Department of Agriculture, Forest Service, Southern Research Station. https://doi.org/10.2737/SRS-GTR-80

Bogetti, J. (2024). *At risk or dismissed? Making the case for designated species at risk legislation in British Columbia* [Master of Science Thesis]. Thompson Rivers University.

Boisvenue, C., Paradis, G., Eddy, I. M. S., McIntire, E. J. B., & Chubaty, A. M. (2022). Managing forest carbon and landscape capacities. *Environmental Research Letters*, *17*(11), 114013. https://doi.org/10.1088/1748-9326/ac9919

Brown, G., Weber, D., & De Bie, K. (2014). Assessing the value of public lands using public participation GIS (PPGIS) and social landscape metrics. *Applied Geography*, *53*, 77–89. https://doi.org/10.1016/j.apgeog.2014.06.006

CavenderBares, J., Balvanera, P., King, E., & Polasky, S. (2015). Ecosystem service tradeoffs across global contexts and scales. *Ecology and Society*, *20*(1). https://doi.org/10.2307/26269709

Chen, B. (2012). *Simulating Landscape and National Scale Carbon Fluxes in Canada's Terrestrial Ecosystems Using CCLASS Model* [PhD Thesis, McMaster University]. https://scispace.com/pdf/simulating-landscape-and-national-scale-carbon-fluxes-in-57m52qp4rq.pdf

Chisholm, P. J., & Gray, A. N. (2024). Forest carbon sequestration on the west coast, USA: Role of species, productivity, and stockability. *PLOS ONE*, *19*(5), e0302823. https://doi.org/10.1371/journal.pone.0302823

Clean BC. (2025). *B.C. OBPS PROGRAM AND REPORTING GUIDANCE* (Province of BC Climate Change). https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/obps/guidance/bc_obps_guidance.pdf

Climate Data. (2021). *Clearwater climate: Weather Clearwater & temperature by month*. Climate-Data.Org. https://en.climate-data.org/north-america/canada/british-columbia/clearwater-770595/

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based solutions to address global societal challenges*. IUCN International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2016.13.en

[Computer software]. (n.d.). [Computer software].

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., & Böhner, J. (2015). System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. *Geoscientific Model Development*, *8*(7), 1991–2007. https://doi.org/10.5194/gmd-8-1991-2015

Costanza, R., De Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., & Grasso, M. (2017). Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services*, *28*, 1–16. https://doi.org/10.1016/j.ecoser.2017.09.008

Council of Canadian Academies. (2022). *Nature-Based Climate Solutions*. CCA Reports; Environment and Climate Change Canada. https://cca-reports.ca/reports/canadas-carbon-sink-potential/

Darvill, R., & Lindo, Z. (2016). The inclusion of stakeholders and cultural ecosystem services in land management trade-off decisions using an ecosystem services approach. *Landscape Ecology*, *31*(3), 533–545. https://doi.org/10.1007/s10980-015-0260-y

DellaSala, D. A., Keith, H., Sheehan, T., Strittholt, J., Mackey, B., Connolly, M., Werner, J. R., & Fredeen, A. L. (2022). Estimating carbon stocks and stock changes in Interior Wetbelt forests of British Columbia, Canada. *Ecosphere*, *13*(4), e4020. https://doi.org/10.1002/ecs2.4020

Dennis M. King, Marisa J. Mazzotta, & Kenneth J. Markowitz. (2000). Dollar-based Ecosystem Valuation Methods. *Ecosystem Valuation*. https://ecosystemvaluation.org/

Diószegi, G., Molnár, V. É., Nagy, L. A., Enyedi, P., Török, P., & Szabó, S. (2025). Testing *treecbh* in Central European forests: An R package for crown base height detection using high-resolution aerial laser-scanned data. *Forestry: An International Journal of Forest Research*, *98*(3), 365–379. https://doi.org/10.1093/forestry/cpae044

DJI. (2024). *DJI Terra User Manual*. https://dl.djicdn.com/downloads/dji-terra/20240118/DJI_Terra_User_Manual_v4.0__EN.pdf

Drever, C. R., Cook-Patton, S. C., Akhter, F., Badiou, P. H., Chmura, G. L., Davidson, S. J., Desjardins, R. L., Dyk, A., Fargione, J. E., Fellows, M., Filewod, B., Hessing-Lewis, M., Jayasundara, S., Keeton, W. S., Kroeger, T., Lark, T. J., Le, E., Leavitt, S. M., LeClerc, M.-E., … Kurz, W. A. (2021). Natural climate solutions for Canada. *Science Advances*, *7*(23), eabd6034. https://doi.org/10.1126/sciadv.abd6034

Dye, A. W., Houtman, R. M., Gao, P., Anderegg, W. R. L., Fettig, C. J., Hicke, J. A., Kim, J. B., Still, C. J., Young, K., & Riley, K. L. (2024). Carbon, climate, and natural disturbance: A review of mechanisms, challenges, and tools for understanding forest carbon stability in an uncertain future. *Carbon Balance and Management*, *19*(1), 35. https://doi.org/10.1186/s13021-024-00282-0

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, *62*(1), 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x

Environment and Climate Change Canada. (2018). *Pollution pricing*. Government of Canada. https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work.html

Environment and Climate Change Canada. (2023). *Social cost of greenhouse gas emissions*. Www.Canada.Ca. https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/social-cost-ghg.html

Esfahani, S. S., Meng, F.-R., & Wong, C. Y. (2026). Species-specific modeling of tree diameter at breast height using tree height and relative density with implications for remote sensing-based forest inventory. *Forest Ecology and Management*, *601*, 123372. https://doi.org/10.1016/j.foreco.2025.123372

Finley, A. O., & Kittredge, D. B. (2006). Thoreau, Muir, and Jane Doe: Different Types of Private Forest Owners Need Different Kinds of Forest Management. *Northern Journal of Applied Forestry*, *23*(1), 27–34. https://doi.org/10.1093/njaf/23.1.27

Forest Trends' Ecosystem Marketplace. (2024). *State of the Voluntary Carbon Market 2024* [Ecosystem Marketplace]. Forest Trends' Ecosystem Marketplace.

Forgues, K. (2023). *A comparison of carbon uptake between four reforestation designs in a community setting* [Master of Science Thesis, McGill University]. https://escholarship.mcgill.ca/concern/theses/v405sh09c

Galik, C. S., Mobley, M. L., & deB. Richter, D. (2009). A virtual "field test" of forest management carbon offset protocols: The influence of accounting. *Mitigation and Adaptation Strategies for Global Change*, *14*(7), 677–690. https://doi.org/10.1007/s11027-009-9190-9

Gómez, R., Aguirre, J., Oliveros, L., Paladines, R., Ortiz, N., Encalada, D., & Armenteras, D. (2023). A Participatory Approach to Economic Valuation of Ecosystem Services in Andean Amazonia: Three Country Case Studies for Policy Planning. *Sustainability*, *15*(6), 4788. https://doi.org/10.3390/su15064788

Gorley, A., & Merkel, G. (2020). *A NEW FUTURE FOR OLD FORESTS A Strategic Review of How British Columbia Manages for Old Forests Within its Ancient Ecosystems*. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stewardship/old-growth-forests/strategic-review-20200430.pdf

Government of Canada. (2019). *Causes of climate change*. Canada.Ca; Government of Canada. https://www.canada.ca/en/environment-climate-change/services/climate-change/causes.html

Goward, T. (2024). *Edgewood Blue*. Edgewood Wild. https://edgewoodwild.org/edgewood-home/edgewood-blue/

Håbesland, D. E., Kilgore, M. A., Becker, D. R., Snyder, S. A., Solberg, B., Sjølie, H. K., & Lindstad, B. H. (2016). Norwegian family forest owners' willingness to participate in carbon offset programs. *Forest Policy and Economics*, *70*, 30–38. https://doi.org/10.1016/j.forpol.2016.05.017

Harmony Foundation. (2023). *The Great Caribou Rainforest Conservation Area*. Draft for a New Protected Area.

Heinze, A., Bongers, F., Ramírez Marcial, N., García Barrios, L., & Kuyper, T. W. (2020). The montane multifunctional landscape: How stakeholders in a biosphere reserve derive benefits and address trade-offs in ecosystem service supply. *Ecosystem Services*, *44*, 101134. https://doi.org/10.1016/j.ecoser.2020.101134

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*, 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

Hrkac, P. (2021). *The Value of Ecosystem Services in British Columbia's Parks and Protected Areas* [Masters of Science in Environmental Economics & Management]. Thompson Rivers University.

Hultman, N., Lou, J., & Hutton, S. (2020). A review of community co-benefits of the clean development mechanism (CDM). *Environmental Research Letters*, *15*(5), 053002. https://doi.org/10.1088/1748-9326/ab6396

International Carbon Action Partnership. (2024). *British Columbia Output-Based Pricing System General Information*. https://icapcarbonaction.com/system/files/ets_pdfs/icap-etsmap-factsheet-70.pdf

Kermagoret, C., & Dupras, J. (2018). Coupling spatial analysis and economic valuation of ecosystem services to inform the management of an UNESCO World Biosphere Reserve. *PLOS ONE*, *13*(11), e0205935. https://doi.org/10.1371/journal.pone.0205935

Klain, S. C., & Chan, K. M. A. (2012). Navigating coastal values: Participatory mapping of ecosystem services for spatial planning. *Ecological Economics*, *82*, 104–113. https://doi.org/10.1016/j.ecolecon.2012.07.008

Kothari, A., Camill, P., & Brown, J. (2013). Conservation as if People Also Mattered: Policy and Practice of Community-based Conservation. *Conservation and Society*, *11*(1), 1. https://doi.org/10.4103/0972-4923.110937

Kulshreshtha, S., Lac, S., Johnston, M., & Kinar, C. (2000). *Carbon Sequestration In Protected Areas Of Canada: An Economic Valuation Economic Framework Project Report 549*. https://www.nswooa.ca/uploads/5/9/6/9/59690537/canadian_parks_council_carbon-sequestration-in-protected-areas-of-canada-an-economic-valuation.pdf

Kumar, L., & Mutanga, O. (2017). Remote Sensing of Above-Ground Biomass. *Remote Sensing*, *9*(9), 935. https://doi.org/10.3390/rs9090935

Lamb, R. L., Hurtt, G. C., Boudreau, T. J., Campbell, E., Sepúlveda Carlo, E. A., Chu, H.-H., De Mooy, J., Dubayah, R. O., Gonsalves, D., Guy, M., Hultman, N. E., Lehman, S., Leon, B., Lister, A. J., Lynch, C., Ma, L., Martin, C., Robbins, N., Rudee, A., … Tang,

H. (2021). Context and future directions for integrating forest carbon into sub-national climate mitigation planning in the RGGI region of the U.S. *Environmental Research Letters*, *16*(6), 063001. https://doi.org/10.1088/1748-9326/abe6c2

Lang, M., Binder, M., Richter, J., Schratz, P., Pfisterer, F., Coors, S., Au, Q., Casalicchio, G., Kotthoff, L., & Bischl, B. (2019). mlr3: A modern object-oriented machine learning framework in R. *Journal of Open Source Software*, *4*(44), 1903. https://doi.org/10.21105/joss.01903

Li, G., Cheng, G., Liu, G., Chen, C., & He, Y. (2023). Simulating the Land Use and Carbon Storage for Nature-Based Solutions (NbS) under Multi-Scenarios in the Three Gorges Reservoir Area: Integration of Remote Sensing Data and the RF–Markov–CA–InVEST Model. *Remote Sensing*, *15*(21), 5100. https://doi.org/10.3390/rs15215100

Lindenmayer, D. B., Hulvey, K. B., Hobbs, R. J., Colyvan, M., Felton, A., Possingham, H., Steffen, W., Wilson, K., Youngentob, K., & Gibbons, P. (2012). Avoiding bio-perversity from carbon sequestration solutions. *Conservation Letters*, *5*(1), 28–36. https://doi.org/10.1111/j.1755-263X.2011.00213.x

Marland, E., Domke, G., Hoyle, J., Marland, G., Bates, L., Helms, A., Jones, B., Kowalczyk, T., Ruseva, T. B., & Szymanski, C. (2017). *Understanding and Analysis: The California Air Resources Board Forest Offset Protocol*. Springer International Publishing. https://doi.org/10.1007/978-3-319-52434-4

Matsuzaki, E., Sanborn, P., Fredeen, A. L., Shaw, C. H., & Hawkins, C. (2013). Carbon stocks in managed and unmanaged old-growth western redcedar and western hemlock stands of Canada’s inland temperate rainforests. *Forest Ecology and Management*, *297*, 108–119. https://doi.org/10.1016/j.foreco.2012.11.042

Mengist, W., Soromessa, T., & Feyisa, G. L. (2023). Responses of carbon sequestration service for landscape dynamics in the Kaffa biosphere reserve, southwest Ethiopia. *Environmental Impact Assessment Review*, *98*, 106960. https://doi.org/10.1016/j.eiar.2022.106960

Menzel, S., & Teng, J. (2010). Ecosystem Services as a Stakeholder-Driven Concept for Conservation Science. *Conservation Biology*, *24*(3), 907–909. https://doi.org/10.1111/j.1523-1739.2009.01347.x

Miller, K. A., Snyder, S. A., & Kilgore, M. A. (2012). An assessment of forest landowner interest in selling forest carbon credits in the Lake States, USA. *Forest Policy and Economics*, *25*, 113–122. https://doi.org/10.1016/j.forpol.2012.09.009

Ministry of Forests. (2024). *Forest Carbon Initiative—Province of British Columbia*. Www2.Gov.Bc.Ca. https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/natural-resources-climate-change/natural-resources-climate-change-mitigation/forest-carbon-initiative

Moomaw, W. R., Masino, S. A., & Faison, E. K. (2019). Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good. *Frontiers in Forests and Global Change*, *2*, 27. https://doi.org/10.3389/ffgc.2019.00027

Nordhaus, W. (2014). Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, *1*(1/2), 273–312. https://doi.org/10.1086/676035

Nowak, D., & Crane, D. (2000). The Urban Forest Effects (UFORE) model: Quantifying urban forest structure and functions. In *Integrated tools for natural resources inventories in the 21st century* (Gen. Tech. Rep. NC-212, pp. 714–720). U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station.

Nowak, D. & US Forest Service. (2021). *Understanding i-Tree: 2021 Summary of Programs and Methods*. https://www.itreetools.org/documents/650/i-Tree_Methods_gtr_nrs200-2021.pdf

Patino, M. (2025). *ECOSYSTEM PRINCIPLES FOR BRITISH COLUMBIA PROTECTED AREAS: STRATEGIC PLANNING AND DECISION-MAKING IN WELLS GRAY PROVINCIAL PARK* [Master of Science Thesis]. Thompson Rivers University.

Piao, S., Ciais, P., Friedlingstein, P., De Noblet-Ducoudré, N., Cadule, P., Viovy, N., & Wang, T. (2009). Spatiotemporal patterns of terrestrial carbon cycle during the 20th century. *Global Biogeochemical Cycles*, *23*(4), 2008GB003339. https://doi.org/10.1029/2008GB003339

Price, K., Holt, R. F., & Daust, D. (2021). Conflicting portrayals of remaining old growth: The British Columbia case. *Canadian Journal of Forest Research*, *51*(5), 742–752. https://doi.org/10.1139/cjfr-2020-0453

Probst, P., & Boulesteix, A.-L. (2017). *To tune or not to tune the number of trees in Random Forest?* https://doi.org/10.48550/ARXIV.1705.05654

Roussel, J.-R., Auty, D., Coops, N. C., Tompalski, P., Goodbody, T. R. H., Meador, A. S., Bourdon, J.-F., De Boissieu, F., & Achim, A. (2020). lidR: An R package for analysis of Airborne Laser Scanning (ALS) data. *Remote Sensing of Environment*, *251*, 112061. https://doi.org/10.1016/j.rse.2020.112061

Secretariat of the Convention on Biological Diversity. (2010). *Global Biodiversity Outlook 3*. https://www.cbd.int/doc/publications/gbo/gbo3-final-en.pdf

Sil, Â., Fonseca, F., Gonçalves, J., Honrado, J., Marta-Pedroso, C., Alonso, J., Ramos, M., & Azevedo, J. C. (2017). Analysing carbon sequestration and storage dynamics in a changing mountain landscape in Portugal: Insights for management and planning. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *13*(2), 82–104. https://doi.org/10.1080/21513732.2017.1297331

Smyth, C. E., Xu, Z., Lemprière, T. C., & Kurz, W. A. (2020). Climate change mitigation in British Columbia's forest sector: GHG reductions, costs, and environmental impacts. *Carbon Balance and Management*, *15*(1), 21. https://doi.org/10.1186/s13021-020-00155-2

Snowball Subject Recruitment. (2017). In M. Allen, *The SAGE Encyclopedia of Communication Research Methods*. SAGE Publications, Inc. https://doi.org/10.4135/9781483381411.n569

Sothe, C., Gonsamo, A., Arabian, J., Kurz, W. A., Finkelstein, S. A., & Snider, J. (2022). Large Soil Carbon Storage in Terrestrial Ecosystems of Canada. *Global Biogeochemical Cycles*, *36*(2), e2021GB007213. https://doi.org/10.1029/2021GB007213

Steenberg, J. W. N., Ristow, M., Duinker, P. N., Lapointe-Elmrabti, L., MacDonald, J. D., Nowak, D. J., Pasher, J., Flemming, C., & Samson, C. (2023). A national assessment of urban forest carbon storage and sequestration in Canada. *Carbon Balance and Management*, *18*(1), 11. https://doi.org/10.1186/s13021-023-00230-4

Stinson, G., Kurz, W. A., Smyth, C. E., Neilson, E. T., Dymond, C. C., Metsaranta, J. M., Boisvenue, C., Rampley, G. J., Li, Q., White, T. M., & Blain, D. (2011). An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008: CANADA'S MANAGED FOREST C DYNAMICS. *Global Change Biology*, *17*(6), 2227–2244. https://doi.org/10.1111/j.1365-2486.2010.02369.x

The Land Conservancy of British Columbia. (2016). *Clearwater Wetland & Wildlife Corridor*. The Land Conservancy of BC. https://conservancy.bc.ca/featured-projects/clearwater-wetland-wildlife-corridor/

Thompson, D. W., & Hansen, E. N. (2012). Factors Affecting the Attitudes of Nonindustrial Private Forest Landowners Regarding Carbon Sequestration and Trading. *Journal of Forestry*, *110*(3), 129–137. https://doi.org/10.5849/jof.11-010

Tolunay, A., & Başsüllü, Ç. (2015). Willingness to Pay for Carbon Sequestration and Co-Benefits of Forests in Turkey. *Sustainability*, *7*(3), 3311–3337. https://doi.org/10.3390/su7033311

Verma, P., & Ghosh, P. K. (2023). The economics of forest carbon sequestration: A bibliometric analysis. *Environment, Development and Sustainability*, *26*(2), 2989–3019. https://doi.org/10.1007/s10668-023-02922-w

Walker, W. S., Gorelik, S. R., Cook-Patton, S. C., Baccini, A., Farina, M. K., Solvik, K. K., Ellis, P. W., Sanderman, J., Houghton, R. A., Leavitt, S. M., Schwalm, C. R., & Griscom, B. W. (2022). The global potential for increased storage of carbon on land. *Proceedings of the National Academy of Sciences*, *119*(23), e2111312119. https://doi.org/10.1073/pnas.2111312119

Chapter 2. The Social Value of Forest Carbon for Stakeholders in the Upper Clearwater Valley

INTRODUCTION

The diverse forest values among stakeholders encompass features of a forest that contribute to human physical wellbeing, non-material dimensions of quality of life, and intrinsic benefits of a forest that exist independently of humankind (Connell et al., 2017). This understanding is crucial to determine a project's potential benefits or challenges because the subjective value of the forest depends on the socioeconomic and geopolitical context and the personal connection to the land. Therefore, acknowledging the benefit of diverse forms of knowledge provides a firmer grounding in real-world operational conditions (Mota-Nieto & García-Meneses, 2024a). The active stakeholder perspectives' involvement not only allows for the resolution of individual concerns but also highlights key moments in decision-making that can significantly impact outcomes (Haddad et al., 2015). By prioritizing stakeholder engagement, projects can foster a more inclusive approach that ultimately identifies pivotal decision-making points (Mota-Nieto & García-Meneses, 2024b). Early consultation fosters trust and relationships between project managers and the community. They also increase the likelihood of community support and participation, thereby reducing potential resistance to risks (Santos-Martín et al., 2013).

The unique geographical configuration of the Valley itself underscores the necessity of this localized study. Its specific combination of mid-successional forested areas in private lands connected to the protected old-growth forests of the Wells Gray Provincial Park creates a territory with substantial, yet vulnerable, carbon sequestration potential. Critically, this potential is already being partially realized by a number of properties that have implemented forest conservation actions that indirectly protect carbon stocks. These pioneering initiatives serve as a model for engaging other properties across the valley. By building on these existing private conservation examples, a broader project can create a vital ecological corridor, connecting fragments of private forests both with each other and with the adjacent provincial park, amplifying carbon storage and biodiversity benefits at a landscape scale.

The understanding of the social value placed on these natural assets by the people who live within and manage this landscape is critical. The success of any carbon project here depends entirely on local cooperation and perspectives, which are shaped by the Valley's social dynamics and economic opportunities. I contend that the Upper Clearwater Valley community recognizes the important ecological value of the forest as a natural capital asset for local livelihoods, wildlife, climate change adaptation, and economic activities. This understanding motivates them to pursue strategies that support the carbon sequestration enhancement in private forest fragments on private properties, despite the sociopolitical challenges and ongoing forestry development in the region. This approach aims to prove that carbon sequestration frameworks that are both ecologically and socially equitable can be proposed as sustainable alternatives for the economic development of rural areas. With the prioritization of the local voices, this study ensures that the specific socio-ecological context of the valley is considered in shaping future decisions.

For that purpose, I identified relevant stakeholders based on previous research in the valley (Bogetti, 2024; Patino, 2025). The main groups to which these stakeholders belong were: academics, local government, external socioeconomic and ecological consultants, and representatives from the main economic sectors: forestry and tourism. I carried out semi-structured and conversational interviews with stakeholders, and recruited additional participants using the snowball sampling method (Kothari et al., 2013). The interviews addressed the socioeconomic dynamics of the valley through the following key questions: 1) Do stakeholders value the forest as a key tool to mitigate climate change through forest carbon sequestration?; 2) What are the socioeconomic challenges a forest carbon project could face in the Upper Clearwater Valley?; and 3) Does the regional government play an actual role in decision-making on forest protection to mitigate climate change? While this research is not an immediate feasibility project for forest carbon protection, it is vital to establish a baseline for potential forest carbon management with local community participation. Understanding the community's priorities and history improves credibility and complements scientific data to design a more realistic carbon project.

INSIGHTS ON FOREST CARBON FROM STAKEHOLDERS IN THE UPPER CLEARWATER VALLEY

The Role of the Forests in Climate Change Mitigation

The government has acknowledged that Canada's forests are crucial to the global carbon cycle due to their vast size and the vast quantities of carbon stored in vegetation, deadwood, and organic and mineral soils (Natural Resources Canada, 2020). Indeed, in the past few decades, progress in forest carbon science has substantially contributed to policy development. Governments and other stakeholders are interested in sustainable forest management to achieve economic, social, and environmental goals, including revenue generation, employment, rural stability, market development, and ecosystem conservation (Smyth et al., 2023).

Despite the government using the best available science to support its policies, it has not achieved most of the intermediate greenhouse gas emission reduction and protected areas expansion goals by 2025 (DellaSala et al., 2022). This can be partly explained by the general population's low awareness of the importance of carbon sequestration for climate change adaptation and mitigation, which is deeply influenced by their scientific, traditional, or empirical knowledge levels. During the interviews, only those who are part of Academia and work for provincial-level organizations were familiar with carbon sequestration and its interconnectedness with people and other ecosystem benefits. Danielle Toperczer, Program Director of the Thompson-Nicola Conservation Collaborative, described:

> *I think that there's tremendous value in continuing to conserve alpine and subalpine ecosystems for whatever value we're looking at, if whether it's carbon sequestration. There's lots of co-benefits there too…biodiversity habitat, soil health and productivity, and cultural values and recreational use.*

In this sense, Toperczer's appreciation considers that ecosystem services cannot be disaggregated since they are increasingly important for measuring tangible and intangible human benefits.

Nevertheless, the general public's understanding of carbon sequestration can be addressed through the lens of relatable benefits daily, such as wildlife habitat areas, water provision, and microclimate regulation, as expressed by the non-academic stakeholders interviewed. These services are deeply interconnected with carbon sequestration, which involves chemical fluxes (water and carbon to the air) to regulate the climate and maintain wildlife habitats (Mota-Nieto & García-Meneses, 2024b). This intricate web of ecosystem services underscores the issue's complexity and importance. Hence, it is urgent to communicate the importance of carbon sequestration as part of the new wave of actions for modern natural threats.

Considering carbon sequestration modelling and research are relatively recent compared to other ecological processes associated with water and materials provision, this is when forest carbon sequestration should be showcased in early education as a key part of climate resilience. Nevertheless, the importance of the Upper Clearwater Valley forest as a strategic location to enhance carbon sequestration was acknowledged by some of the interviewees, such as Chance Breckenridge, Clearwater FireSmart Coordinator (2025), who acknowledged:

> *In Wells Gray, we have a lot of old growth, we're so diverse as far as our biogeozones here. It is such a biodiverse and sensitive area of Upper Clearwater, it's definitely very important to keep a hold on that, keep a tight ship on that conservation.*

Breckenridge specifically mentioned the importance of the Wet Forest as an ecological zone in BC. It encompasses the Interior Cedar-Hemlock zone, where the Upper Clearwater Valley is located, and the Interior Douglas-Fir and Engelmann Spruce-Subalpine Fir zones, which are fed by abundant rain and heavy winter snows. The Interior boasts more productive tree species than any other ecological zone in the province (Thompson-Nicola Conservation Collaborative, 2024).

The Upper Clearwater Valley location is crucial to keep the continuity of the forest within Wells Gray Provincial Park, which currently stores large amounts of carbon. As Catherine Armstrong, Valley landowner and ex-director of The Land Conservancy Trust (2025), explained:

> *A fire swept all the way through here 99 years ago, and brought everything down to 0. So, this is a 100-year-old forest within the valley, is 100% regenerated forest, it's mixed: deciduous and coniferous. I think it is representative of the total value of that buffer in between the two legs of the park.*

Additionally, forest patches on private lands serve as stepping stones in fragmented landscapes, facilitating species movement, enhancing biodiversity, and promoting forest regeneration by facilitating seed dispersal, moderating the local microclimate, and stabilizing the soil. This provides suitable conditions for sapling establishment (DellaSala et al., 2022) that will have a high rate of carbon storage.

Therefore, managing these forest fragments in private lands represents a unique opportunity to increase the carbon sequestration capacity. Trevor Goward, Lichenologist, Upper Clearwater Valley resident (2025), emphasized:

> *When people understand that a forest that looks like a park, in our time, is a forest that has more resilience than a forest that looks all broken up, then I think that there's the very real possibility that something can be made to happen.*

In this sense, Goward highlights the importance of having forests in different successional stages to ensure their resilience by exchanging genetic material to spread resistance genes. A forest with early successional stage zones often contains more fire-adapted species, while mature stages provide structural complexity that can slow fire spread (Antwi et al., 2023). This ecological characteristic is particularly crucial to maintain in the valley, along the private and crown lands, since in the last decades, wildfires and insect outbreaks have diminished carbon sequestration potential, turning the valley into a temporary carbon source.

The interviews on the importance of forest carbon in the study area indicate the need to strengthen awareness of forest carbon storage and sequestration with land managers and local decision-makers. This requires the strategic communication of scientific knowledge appropriate to each stakeholder group's priorities. Although participants generally recognized the value of ecosystem services, carbon sequestration was not commonly framed within this understanding by some participants. Using carbon sequestration as a key benefit provided by forests can enhance stakeholder awareness and support for conservation and management strategies.

Land Management Dynamics for Forest Carbon

Land-use management is a general concern that often arises in projects that aim to maintain healthy forests with the capacity to sequester enough carbon to compensate for local emissions (Environment and Climate Change Canada, 2024b). Generally, the approaches used by each stakeholder to manage their land change according to their interests (Kleinman et al., 2019). However, the integrated landscape-based approach should be a general principle reigning over forest management. This approach pursues the implementation planning and managing human activities that focus on system-wide consideration; on composition, structure, and functions of ecosystems; integration of management objectives across multiple, temporal, and spatial scales; commitment to adaptive management; and dedication to collaborative management (McAfee & Canadian Forest Service, 2008).

While the provincial and federal governments have incorporated the integrated landscape-based approach into their policies, at the local level, stakeholders have underscored a notable difference in the implementation level of the approach for crown land resource exploitation, protected area planning, and private land use. For instance, Stephanie Russell, Conservation Specialist - South Strategic Priorities at BC Parks (2025), asserted:

> *Industries like forestry, range, they fall under the legislation they can use recreational sites and trails, they usually remove trees. They have to either avoid or mitigate these recreational sites and trails. So, it doesn't preclude harvest or removal of trees over those, but it does, if they're designated.*

From her experience, forestry has targeted those areas due to their high value in terms of natural resources. The use of crown lands by forestry demonstrates that requirements must be met if the forest to be disturbed is classified for recreational purposes. In the Upper Clearwater Valley, recreational sites are located within the interior Cedar Hemlock ecozone, characterized by a high side index that grows exceptionally well (Gifford et al., 2022), making it highly productive from the perspective of carbon sequestration enhancement.

As of 2023, BC's land base encompasses approximately 95 million hectares, with about 94% designated as provincial crown land (BC Ministry of Finance, 2023). The province's protected areas system covers over 14 million hectares, representing 14.7% of the total provincial land base (BC Parks, 2024). Additionally, other conservation lands such as wildlife management areas, ecological reserves, recreation areas and conservancies, account for approximately 906,000 hectares, representing 0.9% of the total provincial land base (Province of British Columbia et al., 2023). These percentages indicate that many tenures are non-exclusive, to allow overlapping uses, where the landscape-based approach could be applied for better management. This configuration represents an opportunity for the governments to prioritize crown lands in their conservation plans due to their high ecological value, as they serve as powerful instruments of public forest policy.

Indeed, three sectors account for 98% of the total tenured and protected areas: forestry, tourism and accommodation, and environment and public recreation (Ministry of Forests, Lands and Natural Resource Operations, 2010). In the Clearwater Valley, all sectors are well-represented and have operated for decades with impacts on forest carbon through landscape transformation. For example, roads enable workers and visitors to access areas of interest. Forestry has more extensive and long-lasting environmental impacts due to large-scale tree removal and related activities (Connell et al., 2017). In contrast, the effects of tourism tend to be more localized and can often be mitigated through visitor capacity restrictions and effective management (Li et al., 2024). It is crucial to implement effective strategies in both economic sectors that ensure the protection of forests and the livelihoods of local communities.

For instance, in 1996, Wells Gray Provincial Park and other recreational areas in Clearwater were extended under the expectation of increasing tourism in the area as part of the economic development of the region (District of Clearwater, 2021). This has led to changes in land use, as Randy Sunderman, Economic development consultant and BC Greens (2025), clarified:

> *Clearwater has already given up so much of the local crown area, probably about 30% of the land is a protected area now.*

Sunderman's posture indicates that conflicts regarding the crown land, which could be designated for conservation, tourism, or forestry, have persisted for a long time. Drawing from his personal experience, it appears that certain decisions made by the local government regarding land use are increasingly focused on leveraging forestry, as conservation has been prioritized in previous periods. Other interviewees noted that many residents have been advocating for the protection of the natural environment, a commitment that has persisted for decades following extensive logging by large and local corporations. The ongoing demand for forest protection is crucial, given that the repercussions of past forestry practices have long-term effects that the already designated protected areas cannot fully restore.

Consequently, bringing various alternatives for forest protection and enhancing carbon sequestration are crucial. To consider any alternative viable for conservation purposes under an integrated landscape-based approach, conflicts must preferably be avoided with crown land management. Goward (2025) emphasized that most of the private properties alongside the road in the valley only encompass parcels of 10 acres. The remaining non-protected areas by the province correspond to crown lands designated as recreational sites or used for forest harvesting and management. Under this scenario, using forest patches in private lands offers critical advantages for forest carbon sequestration within an integrated landscape-based approach. Private parcels in the valley can fill spatial gaps between the two sections of Wells Gray Provincial Park alongside the road by connecting them and enhancing ecological corridors. This would reduce the pressure and potential conflicts over crown land by achieving conservation outcomes without needing public land reallocation or new regulations.

Indeed, Alsid Prime, Director of Corporate Services at Clearwater District (2025), suggested:

> *I don't see that there would be any pushback on that (new private forest reserves creation). I don't see it necessarily happening because obviously people want to get some sort of value out of it. It's not like we have a shortage of land in the district of Clearwater.*

In this sense, Prime agreed with the high likelihood of forest protection in the valley's private zones. He also suggests that some people would expect to continue receiving economic benefits from their land, as if they kept using it to generate revenue from forestry, agriculture, or tourism. Nevertheless, according to interviewees, the designation of a new protected area or an extension of an existing protected area does not seem likely in the crown lands of the valley in the short term due to provincial-level priorities.

This interviewee's opinion is supported by the lack of actions taken or planned by the Clearwater District in its municipal development plan. Local decisions for the development of the district's economy are pursuing tourism strengthening and recovery of the local forestry industry (District of Clearwater, 2021). Natural resources in crown lands sustain both economic activities, which implies that natural ecosystems are the main natural asset that local government should manage to guarantee the continuity of its services. Despite this, the Clearwater Development Strategy (2021) does not mention any action to protect or manage additional forested areas that allow forestry and tourism economic sustainability.

Although residents are aware of the opportunities for forest restoration in both crown lands, Roland Neave, Wells Gray Tours Owner (2025), argued:

> *There is a long-standing dispute between the residents and the logging going back to the late 90s. So, the areas that are mostly in dispute are now controlled by the Wells Gray Community Forest.*

This situation reveals the diverse perspectives that valley stakeholders have on the use and management of ecosystem services and local governments' priorities in recent years for the district's economic development.

The implementation of conservation strategies that foster collaboration between public and private stakeholders is essential to address biodiversity loss and climate change. This includes programs for strategic acquisition and incentives to align private lands with broader watershed and landscape restoration goals (Environment and Climate Change Canada, 2024b). Managing crown lands is crucial to create interconnected forest corridors that enhance carbon sequestration. The government of BC is modernizing land use planning in partnership with First Nations to balance population and economic growth with ecosystem health and resilience to climate challenges (Government of British Columbia, 2025c). The benefits of these strategies for private landowners and improved land use will likely only be experienced in the long term.

Forestry Impacts on Carbon Sequestration in the Valley

The forest industry was once the most important economic activity for rural communities in BC. Its footprint has been in a long and steady decline since the 1980s (District of Clearwater, 2021). Several environmental and socioeconomic reasons led to the closure of mills in recent decades. These include: beetle-killed timber running out, higher intensity and severity of wildfires, regulatory shifts like old-growth forest moratoriums, high harvesting fees, and rising pressure to return land to Indigenous stewardship (UNIFOR, 2024).

The provincial government decided to involve local communities more directly in forest management through a network of Community Forest Agreements, a type of forest tenure introduced in 1998 (Haley & Nelson, 2007). This policy was also a direct response to give back the territory and its natural resources to local communities, since they expect to manage land within a framework that meets local needs. As Nancy Flood, Emeritus Professor at Thompson Rivers University and Kamloops Naturalists Club President (2025), stated:

> *There are lots of forestry private groups, including First Nations, that own forest licenses in the valley, and I think that's the biggest issue. The community forest*

> *is part of that, I think they are trying to do it sustainably, economically and ecologically.*

For Clearwater, particularly, the decrease in the industry presence was unprecedented. In 2019, the last large sawmill in the Clearwater area, Canfor's mill, closed, losing 175 direct jobs. With most of the fibre now moving outside the community (District of Clearwater, 2021). There was a time when the Wells Gray Community Forest Corporation took on even greater importance in the area. This corporation was formed in 2006 and is a citizen-owned forest in Wells Gray Country. It manages 13,148 hectares of land with an Annual Allowable Cut of 29,900 cubic meters of timber, providing jobs and revenues for the community (*Wells Gray Community Forest*, 2023).

The Wells Gray Community Forest Corporation states that its mission is to manage the forest, focus on long-term sustainability, environmental stewardship, and support local industries (*Wells Gray Community Forest*, 2023). They utilize the framework that the Canadian Council of Forest Ministers developed to achieve this. It consists of six criteria and 46 indicators that define and monitor sustainable forest management in Canada. The criteria are: Biological Diversity; Ecosystem Condition & Productivity; Soil & Water Conservation: Role in Global Ecological Cycles; Economic & Social Benefits; and, Society's Responsibility (Canadian Council of Forest Ministers, 2022).

These principles reflect a vision aimed at balancing environmental integrity, economic viability, and social well-being in decision-making related to harvesting. Despite this, the Wells Gray Community Forest Corporation does not recognize carbon sequestration as a strategic principle (G. Brcko, personal communication, February 4, 2025). This approach would require leaving a large part of the licensed area not recently disturbed to capture carbon and offer habitats for wildlife, and avoid sudden changes to ecological processes. The Wells Gray Community Forests acknowledges the importance of forest protection and, if feasible, intends to lock boundaries around areas adjacent to the park to recognize their high value, mature wood, and the importance of public access (G. Brcko, personal communication, February 4, 2025). Conversely, according to other interviewees not linked to forestry, residents and recreational area users perceive that the past and current logging results are inconsistent with the community forest corporation's posted criteria for designing its harvesting plan. As Tom Dickinson, Biologist - TRU Emeritus professor (2025), declared:

> *There is uncertainty regarding whether the community forest's current harvesting rate aligns with sustainable growth models. Traditionally, forest management involved rotating harvests across designated patches, ensuring each area reached a specific age before being cut again. If the designated age for harvesting is set too short, the ecosystem may not fully recover or sustain its ecological functions.*

Even selective logging creates openings in the forest canopy and increases the amount of "edge habitat". This is the boundary between the forest and the cleared or disturbed area. Forest edges are hotter, drier, and windier than the forest interior. This "dryness" and heat can penetrate deep into the protected area, stressing species that rely on cool, moist, stable conditions and letting generalist species conquer altered environments (Haddad et al., 2015). From the socio-political perspective, the continuity of forestry in areas with high ecological value, like the valley, can weaken the natural boundary. This is a socio-political and economic risk. The existence of logging infrastructure and a local workforce dependent on the industry can create powerful lobbying forces to open up the protected area itself for resource extraction, arguing it is necessary for jobs and the local economy (Bernard et al., 2014). Thus, the use of forest resources should prioritize meeting local community needs and developing sustainable economic alternatives instead of focusing on intensive forestry. As Goward (2025) states:

> *A populace that sees the advantages of interacting with their forest ecosystems in a way that gives resilience. I think that would have long-term ramifications for the economy of the area, but through tourism, not through logging.*

Since the Wells Gray Community Forest is the only company harvesting in this area, it is important to note that they have a smaller portion of land to harvest than the licenses that big companies used to exploit. From this perspective, the provincial government's decision to allocate most of the unharvested crown lands to the community forest corporation reduced the local environmental impacts. As Sunderman (2025) expressed:

> *You're dealing with a community that still has a lot of expertise and experience in forestry. And the other thing is they've lost so much there, and there are aspirations of getting back some of the things that they've lost…*

Balancing social responsibility with the local community's needs, such as maintaining employment and investing in social and cultural initiatives, alongside environmental commitments, presents a substantial challenge. Furthermore, the local community has deep connections to the forestry industry, which has recently experienced economic hardships due to international tariffs (District of Clearwater, 2021). Despite a strong recognition of the importance of forest conservation, the local support for forestry remains substantial in the region.

From 2000, some public policies across the country have seen a shift away from economic concerns towards greater emphasis on environmental protection, biodiversity, endangered species habitat and ecosystem integrity, that were barely in the lexicons of forest policymakers and managers a few decades ago (Haley & Nelson, 2007). There are several recent and ongoing initiatives in BC to advance adaptation in the forest sector. Since 2015, BC Ministry of Forests, Lands and Natural Resource Operations has played a strong role in setting objectives for resource management and adaptation, to develop a climate change strategy and facilitate adaptation efforts led by First Nations, community forests, and forest professionals (Gifford et al., 2022).

This diversification of strategies to keep the forestry industry economically sustainable at a smaller spatial scale will inevitably push some people who have lost their jobs in forestry to rely on different economic activities. Measuring economic diversity and regional income dependency as a result of crown land activity provides insight into the social and economic resilience of the province and its diverse regional landscape. The more diversified a community’s economic base, the more likely it is to sustain itself through volatile economic times (Ministry of Forests, Lands and Natural Resource Operations, 2010).

Forest Carbon and Tourism

Tourism fundamentally derives its benefits from the recreational ecosystem services provided by forests, leveraging their aesthetic and experiential value for economic gain. The long-term viability of this relationship hinges critically on the rate and manner of touristic development, especially in areas of high ecological value. This is underscored by research that demonstrates that nature-based tourism relies significantly on the aesthetic value of natural landscapes, a value directly threatened by unregulated tourism and land use changes (Iversen et al., 2021). The challenge is particularly salient in regions where governments promote intensive economic growth through increased visitor numbers in rich natural areas, as the Canadian federal government has done (Government of Canada, 2025a). The complex relationship between these factors underscores the necessity of an ecosystem services framework within land-use planning to identify trade-offs and promote sustainable tourism practices that do not compromise ecological integrity (Li et al., 2024).

Tourism in Clearwater has been developed as an industry with a low impact on nature, as most visitor-appealing activities rely on observation and enjoyment of the forests. For example, some tourism operators offer guided wildlife and birdwatching tours in the North Thompson Valley, which focus on species such as bald eagles, bears, bighorn sheep, and loons (Davison, 2023). Wells Gray Adventures offers low-impact adventures: hut-to-hut hiking, canoe trips, and nature walks that use existing trails and waterways (Briggs & Eakins, 2024). Similarly, numerous water tourism operators run interpretive canoe, kayak, and boat tours on Wells Gray’s lakes and the Clearwater River (Interior Whitewater Expeditions, 2025).

These activities indirectly contribute to the conservation of carbon stocks as they avoid building new roads or clearings, minimize soil disturbance, and maintain the canopy integrity through hiking, paddling, or guided walks. It is essential to look at where these activities are being conducted in the valley. As Russell (2025) clarified:

> *Some of them (tourism operators) use their own private land, the park, Crown Land that's been designated as a rec site. So, these areas already exist, they are not legally protected areas, but formally protected areas by private landowners.*

Her point supports the statement that tourism has taken place in all the spatial settings the valley offers visitors, including various types of land uses. This indicates that the protection of forests is already occurring, thereby envisioning the capacity and potential of tourism in the area. Such expansions secure forest landscapes for tourism and lock in their climate benefits in areas other than protected areas, as the land use will allow for other activities according to its spatial configuration.

Several aspects should be considered when planning a new forested area that combines tourism and conservation. These include the landscape's aesthetic appeal to attract tourists. As Dickinson (2025) proposed:

> *Some people won't come back for a second visit because they didn't like what they saw the first time. And maybe if the visitors are just seeing that there is a change, not only in the park but around the surroundings, they will say this place has a higher value.*

His insight partially reveals the current diversification of land use that the valley faces in crown lands, which will inevitably alter the landscape as it approaches protected areas. In general, forest fragmentation can alter the aesthetic appeal of natural landscapes, which can affect activities such as hiking, birdwatching, and photography, reducing the quality of recreational experiences (Li et al., 2024). This disruption may lead to a loss of scenic value in the area, which tourism operators highly value. As Flood (2025) discussed:

> *There's a certain number of people who like to go to places that are protected and have a scenic appeal. We could probably increase more wilderness tourism if we can get protected a reasonable number of trees, a balanced forest.*

Flood’s thought elucidates how discontinuity can be perceived by not only the local community in the aesthetic dimension but also has impacted ecosystems' capacity to deliver services.

Fragmented forests reduce biodiversity, making it challenging for ecotourism operators to provide wildlife-viewing experiences. For instance, habitat fragmentation has been shown to reduce biodiversity by 13% to 75%, impair key ecosystem functions and diminish the appeal of tourists seeking rich wildlife encounters (Haddad et al., 2015). In addition, as the valley encompasses private lands embedded into crown lands and designated protected areas, the discontinuity in the forest has also caused detriment to the water supply, soil quality and disrupted nutrient cycles (Haddad et al., 2015). These phenomena affect the natural environment, community livelihoods, and tourism. Many tourist activities depend on the health and stability of the forest and the water supply for private properties, especially those with accommodation and tourism infrastructure.

Another natural consequence of forest fragmentation is the trigger of successional processes, which involve colonizing generalist plant species in recently logged areas. Gy Ovenden, Ecology consultant and Former Wells Gray Provincial Park Guide (2025), identified an advantage for tourism when a successional stage started in the valley:

> *The forest in the valley makes really attractive for us (touristic guides) to take people through because it has a lot more deciduous trees. So, it's better for diversity of bird and plant life. There are certainly opportunities to improve wildlife viewing in that area.*

Ovenden has observed that changes in wildlife movements can enhance tourism in areas impacted by wildfires. In many cases, deciduous tree species become dominant after disturbance, altering the entire dynamic of the area, as each plant species has specific evolutionary relationships with pollinators, changing the trophic chain and carbon cycling (Chen et al., 2024; Mina et al., 2022; Payne et al., 2019). In contrast, human disturbances, such as logging and agriculture, can interrupt these natural recovery processes, making ecosystems more vulnerable to additional disturbances (Kleinman et al., 2019).

In opposition, Neave (2025) explained that:

> *Most of the land in Upper Clearwater are small acreages. So, there isn't a whole lot there that would expand tourism. I can't think of any properties in the valley that could have a tourism element other than bed and breakfasts or lodging.*

His perception aligns with the notion that only large land extensions can substantially enhance ecosystem services or create viable tourism businesses. The creation of a large corridor with connected forest patches along multiple land-use parcels in the Upper Clearwater Valley could serve tourism to generate different alternatives for hiking routes or even include educational tours. From a visually appealing perspective, a notable corridor visible from the lookout spots in the valley could add value to tourism. Indeed, visitors and local governments pay close attention to the harmonious integration of architectural style and surrounding environments, where forestry, agriculture, and conservation coexist, to promote a tourist site (Connell et al., 2017; Howe et al., 2014a).

Wells Gray Provincial Park is a remarkable asset for the tourism sector in Clearwater, showcasing remarkable natural features that appeal to a diverse range of visitor markets from regional, national, and international backgrounds (District of Clearwater, 2021). Despite BC Parks' commitment to conservation, the current management plans for Wells Gray Provincial Park are outdated and do not adequately reflect the park's tourism potential or the economic opportunities it could offer local communities. There is a clear opportunity to strengthen both tourism and conservation efforts—especially in the buffer zone, where forest patches could enhance ecological connectivity. At present, however, the municipality's emphasis on forestry may limit the development of future tourism initiatives in the region.

Evaluation of Governmental Support for Forest Carbon Sinks

Various government authorities in Canada have different responsibilities and scopes regarding jurisdictional scale in support of forest carbon sequestration as a nature-based solution for climate change mitigation and adaptation. From this perspective, each level of authority plays a particular role in the forest carbon enhancement, to provide general guidelines or local regulations to assess the viability of creating a managed or conserved area that increases the forest's carbon sequestration capacity.

The federal government provides science and policy expertise on national forest sector issues, funding for nature-based climate solutions, and access to models like CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector), used to estimate carbon sequestration potential, and lastly, reports on carbon stocks and fluxes in forests as part of Canada’s Greenhouse Gas Inventory (Natural Resources Canada, 2024). Access to federal government data provides a starting point for understanding the current state of carbon storage and sequestration in a particular area based on national-scale models.

The provincial and territorial governments have authority over the conservation and management of provincial and territorial lands through the development and implementation of climate policy. Notably, the BC Ministry of Forests has implemented initiatives that fund forest carbon, such as the Forest Enhancement Society of BC (Government of British Columbia, 2024a), facilitates the participation of carbon projects in the carbon market, manages rights for timber harvesting, and sets conditions that can incentivize sustainable practices and carbon storage (Ministry of Forests, 2020). The Ministry of Environment and Climate Change Strategy tracks carbon emissions and sequestration in the Land Use, Land Use Change, and Forestry sector and oversees protocols for forest carbon projects under BC’s Carbon Neutral Government Program and compliance market (Government of British Columbia, 2024a).

BC’s municipal, regional, and Indigenous governments are important drivers of climate change adaptation. They may incorporate forest conservation and carbon sequestration into land use planning and climate adaptation strategies. They are well placed to identify local vulnerabilities and address equity issues, implement appropriate actions and integrate disaster risk reduction and climate change adaptation (Council of Canadian Academies, 2022a). Local governments still face numerous challenges, such as the lack of mandated use of historical and projected climate change information and specific change scenarios in the decision-making of adaptation strategies (Gifford et al., 2022).

Government reporting on forest management responses to climate change comes from industry sector reporting. There is a scarcity of literature specifically reporting on the forest sector, as only a minority of researchers differentiate between site, stand, and landscape-level approaches to manage climate impacts in the forest (Antwi et al., 2023). Local governments bear the direct impacts of climate change and must address their communities' unique needs with limited resources and legislative authorities. The District of Clearwater has committed to promote cooperation in the management of crown land areas and resources for multiple and public uses, conserve wildlife habitats and environmentally significant areas, and manage hazard lands to protect resources and avoid their inappropriate use (District of Clearwater, 2023).

The protection of the environment and natural capital in rural communities such as Clearwater can be realized through effective land use management and the adoption of nature-based solutions for climate change adaptation. A critical factor in this process is securing the necessary financial resources, as well as the willingness of decision-makers to prioritize these strategies and the support of the local community. As Sunderman (2025) stated:

> *The district of Clearwater doesn't really have the levers to go outside of their district to be involved, even though they can advocate for how Wells Gray Park is run. Municipal governments really rely on property taxes to get new revenue*

Sunderman emphasizes that there are decisions that could affect the Clearwater community but are made at higher levels of government. These decisions influence the development and implementation of programs that respond to jurisdictional restrictions and the municipality's budget. These financial challenges are compounded by the hurdles that are placed on local governments through legislation that has, at times, failed to keep up with the types of issues, such as climate change, that modern cities and towns in BC are grappling with (Carrie Moffatt, 2020).

In addition to the insufficient financial capacity of municipal governments, some policies can serve as either enablers or barriers to climate change adaptation. Prime (2025) expressed the possibility of the implementation of a carbon storage enhancement solution for climate change in the Clearwater District:

> *Natural asset management is my role, but there was no political will to recognize those forest areas as assets—for carbon storage—that we should protect.*

Prime identifies a barrier coming from mismatched priorities among government decision-makers that impacts climate change adaptation strategies. This issue has been highlighted by the Community Charter's stipulation that environmental protection is a shared jurisdiction between provinces and municipalities. Unlike most municipal laws in Canada, bylaws under this authority need ministerial approval, and this limits local governments' autonomy (Carrie Moffatt, 2020). As a result, resource managers lack assurance of support for their adaptation decisions.

Apart from that, it is essential to analyze how land managers operate under government authorities' rules based on their role. Private forest owners, whether they are small woodlot owners, often have their own management objectives (Smyth et al., 2023). In contrast, forestry companies have environmental and operational responsibilities through legal arrangements with provincial and territorial governments. In cases where industry operates on crown land, differences in perspectives between the government and the forest industry can influence how climate-related risks are assessed and which industry incentives can mitigate those risks (Gifford et al., 2022).

George Brcko from the Wells Gray Community Forest Corporation emphasized that BC is transitioning to a landscape-level planning approach, which implies a significant change in forestry practices. This new framework will discourage logging from boundary to boundary to encourage alternative practices that promote ecological connectivity in the Upper Clearwater Valley. It is important to note that historically, industry and government have prioritized short-term interests, often driven by high discount rates (Gifford et al., 2022). Even though the corporation's operations will be subject to government approvals, compliance, and enforcement, records have shown that laws tend to favour forestry due to its economic importance in international tariff crises and climate change fight like the present one (Personal communication with T. Dickinson, 2025).

Even when governments use a lower rate to evaluate future costs and benefits, they often still undervalue the future, which makes it challenging to justify government investments due to serious long-term risks (Canadian Council of Forest Ministers, 2022). This short-term focus is reinforced by the region’s historical dependence on resource extraction, which has shaped local institutions and limited their ability to adapt or diversify (Connell et al., 2017). As a result, many workers remain tied to traditional resource-based jobs and face challenges to transfer their skills to new sectors. To address these systemic constraints will require a shift in economic structures to empower municipalities with greater access to resources and legislative authority, thereby enhancing their ability to meet climate targets and respond effectively to the climate crisis (Carrie Moffatt, 2020).

In this context, effective climate change action depends on collaboration between scientists and policymakers to integrate diverse perspectives. The long-term nature of forestry programs, however, makes it difficult to measure progress over time. To overcome these challenges and avoid inaction amid rapid change, it is essential to turn both to scientific and traditional knowledge in ways that produce concrete strategies that protect Canada's forests and forest-dependent communities (Antwi et al., 2023). Notably, with their smaller scale and localized reach, local governments are uniquely positioned to act quickly and responsively to climate change's impacts on their respective regions (Carrie Moffatt, 2020).

The Willingness of the Local Community to Enhance Carbon Sequestration

The Clearwater municipality's most important economic activities are agriculture, tourism, and forestry. The distribution of the labour force is as follows: 24% for sales and service occupations, 16% for trades and transport occupations, 14% for natural resources and agriculture occupations, and 8% for both natural and applied science, as well as education occupations (Government of Canada, 2016). The land use categories mapped in the valley include agriculture, wetlands, young forests, selectively logged areas, and timber harvesting within the past 20 years or older (Province of British Columbia, 2025).

Given the socio-demographic information and the scope of this research, I anticipated that conflict could occur between different forest functions at the stakeholder level. Subsequently, I asked the participants if there was any potential land-use conflict between the land managers. In the hypothetical case of a new forested area established for conservation, a better understanding of these tensions may help anticipate potential conflicts arising from new ecotourism developments, improve stakeholder communication, and, hopefully, mitigate conflicts.

The population of the Upper Clearwater Valley is less than 500 people (District of Clearwater, 2021). Most of the private landowners living there use this kind of property for residential and small-scale agricultural purposes. 59% of crown land in the valley is used for forestry, under the licenses of the Wells Gray Community Forest Corporation (BC Data Catalogue, Land Ownership and Status Provincial Map Layer, 2025). Importantly, several new landowners in the valley belong to a different generation from those who grew up with forestry as the main economic activity in the valley. According to the 2016 Census in Clearwater, most of its residents are 40–69 years old, with a median age of 47.5 years. People in this age group grew up before climate change and sustainability were central topics, even though they have a strong connection to land, farming, or resource industries. Therefore, some interviewees feel a moral responsibility to leave a habitable planet for future generations, which motivates them to support environmental action.

The Upper Clearwater Valley offers a natural landscape that can be utilized to obtain diverse benefits through landscape-based management. Most interviewees agreed that the landowners near the park either live there because they share a pro-nature mindset or are currently using the territory. They are cautious about changes that seem to threaten their livelihoods. They are aware of the valley's invaluable natural resources and its potential to guarantee economic stability through less impactful activities such as tourism.

Given this deep-rooted interest in the forest, many landowners are exploring practical ways to maintain their natural surroundings while enhancing carbon sequestration. Landowners have planted longitudinal forest fragments to guarantee the privacy of the property (Chance Breckenridge, personal communication, January 22, 2025). This demonstrates that residents of the valley value their surrounding forests in equal regard to their land. It also presents an opportunity to further boost carbon sequestration through the implementation of live fences. Utilizing native or well-adapted tree and shrub species and land-use practices in these live fences can not only increase carbon storage but also improve soil health and offer various ecological benefits (Aryal et al., 2022).

Studies by the United States Department of Agriculture have found that the presence of forests and wild areas can contribute significantly to community character, cultural and economic diversity, resource dependence, attractiveness to business, quality of life, and civic leadership (Wilson, 2019). The interviewees highlighted these profound benefits in promoting community cohesion, stability and resilience because of the interconnectedness of ecological health and social well-being. They also recognized that the economic dimension is paramount. When local industries thrive, environmental sustainability and cultural vitality tend to flourish as well.

Understanding the community's needs and values can help anticipate these issues and co-develop solutions. For instance, potential participation in monitoring and opportunities for local employment in restoration or conservation work can be part of the solution. Armstrong (2025) expressed some of these concerns:

> *In private land, some of the owners do forestry or ranching. Both are historical heritage features, since when the pioneers who came here 102 years ago.*

She underscores how some valley residents historically have made money from their vegetation cover clearing indirectly, whether by keeping the forest intact or managing it for agricultural systems. Most of the interviewees manifested an explicit interest in protecting the forest while contributing to the economic growth of the valley. It is then imperative to economically support environmental initiatives. Forest carbon projects provide financial incentives for forest conservation and restoration efforts. They can also raise concerns about job security, restrictions on land use, operational management and long-term profitability.

Two forest carbon project scenarios (with and without carbon offsetting) were presented to the interviewees to gather their insights and anticipate conservation challenges in the valley. The first scenario presented comprised only conservation and private management of forest fragments and corridors, while the second one included the generation of carbon credits, each representing a metric ton of carbon dioxide removed from the atmosphere. During the interviews, four main topics emerged regarding the viability of either of the two project scenarios: 1) whether the demographic shift in the valley population could favour the development of the project; 2) personal limits for the commodification of forest conservation; 3) the feasibility of the project with the current forest size in private lands; and, 4) the local community's stance on the project. In general, the interviewees believed there would be a positive response to a forest carbon project in the valley that was primarily oriented to a carbon offset project. This was in part due to how private landowners who value the forest fragments within their properties could benefit financially through conservation and management of the landscape.

Indeed, Breckenridge (2025) informed that some conservation efforts are already ongoing in the valley through the implementation of FireSmart actions:

> *People are doing some selective thickening and spacing on their properties and trying to mitigate the fire hazard and still retain most of the crown closure.*

The insights from Breckenridge and the majority of the interviewees highlight a critical observation: landowners have, in essence, contributed to enhancing carbon sequestration indirectly. This is particularly noteworthy because there are already dedicated individuals actively engaged in the stewardship and preservation of forests across private lands, on a smaller scale. The FireSmart strategy (Canadian interagency Forest Fire Center, 2025) is a set of principles and actions designed to reduce the risk of wildfire damage to homes and communities**.** While its primary goal is not carbon sequestration, its implementation directly and indirectly contributes to it by promoting resilient forest ecosystems that are better at storing carbon over the long term.

Direct FireSmart actions, such as creating defensible space and conducting strategic forest thinning, directly contribute to carbon sequestration by protecting existing carbon sinks. These measures remove dense underbrush and ladder fuels, which reduces the risk of high-intensity wildfires that would otherwise combust mature trees and soil carbon, releasing vast stores back into the atmosphere (Canadian Interagency Forest Fire Center, 2025). By preventing this catastrophic carbon loss, FireSmart actions ensure large, carbon-rich trees survive, and the resulting healthier, less dense forests allow the remaining trees to grow more vigorously, enhancing their capacity to pull carbon from the air. Indirectly, these practices help the landscape recover more quickly after a fire by preserving seed sources and soil integrity, allowing the forest to return to being a carbon sink sooner (Pais et al., 2020). Furthermore, by preventing stand-replacing wildfires, FireSmart secures the long-term potential of the forest to continuously sequester carbon (Canadian interagency Forest Fire Center, 2025).

There is a crucial factor that makes a forest carbon enhancement project socially viable for the Upper Clearwater Valley in the words of Prime (2025):

> *I think that one of the biggest key takeaways is definitely a shifting demographic and mentality, the logging industry used to build this town and then, in 2017, the mill shut down.*

Prime accentuates that the generational shift in the valley population represents a higher probability of project acceptance as a forest carbon offset, considering the urgency to find better economic opportunities to safeguard their territory and manage it to accumulate even greater benefits from the forest in the future, in the context of climate change. Ovenden (2025) also elaborated:

> *Clearwater is a community built primarily on the forest industry, so people generally view the forest as something that can be monetized and exploited. So, in a way, the carbon offset project is offering a way of monetizing the value of forest without actually removing the trees.*

His perspective on the opportunity to implement a forest carbon offset project illustrates how some landowners might initially perceive the trade-offs of participating in this project, to balance the economic benefits a different practice could provide against the personal value they place on the forest.

The possibility of developing a forest carbon enhancement project without relying on the figure of a carbon offset project was broadly considered by the interviewees, considering their current desire to work independently for wildfire protection. Still, the non-offset-based policy and incentive strategies for enhancing carbon sequestration focus on direct support, regulation, land-use planning, promotion of low-carbon farming techniques, and ecosystem stewardship from the government. There are some provincial options available, such as Forest Landscape Plans (Government of British Columbia, 2025d) and Incentives for Agricultural Land Use Changes (Ministry of Agriculture and Food, 2022). Alternatively, there is funding for operations and maintenance activities on lands owned and managed by non-governmental organizations in BC (Habitat Conservation Trust Foundation, 2025).

While most interviewees were open to government or Non-Government Organizations (NGO)-led management under these programs, they also raised concerns about tight timeframes, intense grant competition, and how long-standing the program would be in the medium term. As indicated by Dickinson (2025):

> *I think ecosystem services payments or tax relief are part of an idea that, it's ebbed and flowed with the politics. You could see it very clearly that the best conservation came when economic times were the best.*

His perspective mirrors a broader trend that has emerged, particularly in light of global political uncertainty and the challenges imposed by economic inflation, as he states. Given this context, it becomes clear why individuals prefer privately managed initiatives that operate independently from government supervision when it relates to their property’s resources. This approach provides them with a greater sense of economic security and stability.

The biggest concern expressed by the interviewees was the feasibility of a carbon offset project at the current spatial scale. If it were a larger area, a higher number of carbon credits would be issued to maintain the project's operations.

Generally, the current size of the forests already protected in private lands outside the provincial park was perceived as insufficient to obtain the financial resources to implement all the restoration, reforestation, and management practices necessary to improve the forest and enhance its carbon sequestration capacity.

However, there is hope in the way the project could be shaped, as Toperczer (2025) suggested:

> *When I think about larger parcels, they hold tremendous value. But for landscape connectivity, every parcel matters. Parks are key areas that corridors need to connect to and feed back into. If you can combine several 10-hectare parcels into one project, you can create more value*

Land Trusts and organizations like BC Parks (Personal communication with Stephanie Russell, 2025) share the approach of starting from small parcels and using them as stepping stones to create forest corridors or fragments that can be ecologically functional and support all the ecosystem services. Thus, a forest functions as a system with several living individuals interconnected rather than as an agricultural parcel.

According to the carbon offset project verifier organization Verra, there is not a strict minimum area to implement a project, but economic feasibility usually dictates a minimum of 100–200 hectares (250–500 acres) for forest projects. Smaller projects may not generate enough credits to offset monitoring and verification costs (Verified Standard Carbon, 2020). The Upper Clearwater Valley community can consider various options to create a large area by uniting strategic portions of multiple landowners' properties. For this purpose, Neave (2025) stated:

> *We own 300 acres up there. So, we're certainly very interested in seeing that the mountainside is preserved because we get our water from there.*

Collaborations have the potential to create a more effective land use strategy. Involving a prominent member of the community, who also plays a crucial role in the local tourism economy, would provide strong backing for the project. Therefore, his participation could encourage other landowners to participate, foster wider interest and support for the initiative.

To expand the project to additional properties, the Wells Gray Community Forest Corporation has reaffirmed its commitment to forest conservation that benefits the local community. While certain areas within their crown land licenses are logistically difficult to harvest, they play a vital role in watershed protection and function as wildlife corridors. Yet, the terms of their timber supply agreements restrict participation in carbon offset projects (G. Brcko, personal communication, February 4, 2025). Community Forest Agreements primarily focus on timber rights, and do not automatically confer the right to monetize atmospheric benefits, such as carbon sequestration. To participate in carbon offset projects, communities must secure an Atmospheric Benefits Sharing Agreement with the provincial government (Cline, 2024). This remains a clear barrier.

With the potential addition of new land, coupled with the existing protected areas owned by The Land Conservancy Trust, Thompson Rivers University, Edgewood Blue, and forest fragments from various private properties along Clearwater Road, there is an opportunity to establish a substantial and interconnected habitat. This expansive area would not only significantly enhance carbon sequestration efforts but also function as a crucial corridor for wildlife movement to allow various species to thrive and navigate safely between habitats.

CONCLUSION

The social value of forest carbon in the Upper Clearwater Valley is integrally tied to the diverse perspectives and needs of stakeholders invested in these forest fragments, which are located on both private and crown lands. The insights gathered from the interviewees underscore that stakeholders not only view forests as critical tools to mitigate and adapt to climate change through carbon sequestration but also recognize their role in supporting the valley's economic activities. Due to jurisdictional constraints on land management and interviewees' perceptions, the use of private land proved to be the most viable choice for creating a forest corridor.

Notably, the Clearwater district's FireSmart program has been implemented on some private lands, which indicates a precedent of landowners interested in landscape-based management and, thereby, enhancing carbon sequestration. FireSmart actions shift the forest paradigm from one of dense, fire-prone stands vulnerable to catastrophic carbon loss, to one of resilient, lower-density stands dominated by large, healthy trees. In essence, FireSmart not only increases carbon sequestration; it secures the vast amounts of carbon already stored in forests and ensures they can continue to sequester carbon for generations to come.

The reinforcement of the FireSmart program with a carbon sequestration approach would undoubtedly increase the awareness of this ecosystem service and would facilitate the implementation of a more complex project that could cover a larger area. To understand why this multifaceted value is essential to inform project implementation and enhance stakeholder engagement can lead to improved communication and the potential resolution of conflicts arising from varying land-use priorities. It's a critical investment in both community safety and climate stability.

The dual roles of forestry and tourism play a crucial part in expanding high-carbon sequestration areas within the valley. Currently, local forestry companies manage approximately 60% of the crown land in the valley, which is linked to Wells Gray Provincial Park and private forest patches along the roadway. The extent of the area licensed for logging constitutes a substantial portion of the forest that can be strategically managed to enhance carbon stocks, as it fosters ecological interconnectedness. Through the revision of their current harvesting practices and adoption of landscape-based approaches as outlined in the province's sustainable forestry practices, these companies could make a substantial contribution to forest resilience and connectivity. In parallel, tourism would thrive as it capitalizes on the private forest fragments in the buffer area of Wells Gray Provincial Park. This unique landscape allows for a combination of low-impact recreational activities and conservation, to create a rich experience for visitors while simultaneously in support of health ecosystems.

The involvement of regional government in decision-making processes plays a critical role to shape perceptions and actions regarding forest conservation. Stakeholders desired more collaborative engagement and transparency from local authorities, which is vital to foster trust and collective action. By recognizing the intrinsic and socioeconomic values of forests, stakeholders may be more inclined to support initiatives to mitigate climate change. The successful execution of the Upper Clearwater Valley forest carbon projects will depend on a comprehensive approach that harmonizes environmental objectives with community needs to achieve a balance of sustainable management of forest resources.

The insights gathered from landowners, particularly the older generation with a strong bond with regional lands, reveal a desire for innovative solutions that support environmental stewardship with consideration of economic sustainability. By exploring options such as live fences and forest patches within private properties interconnected along the valley to enhance carbon sequestration, the general perception is that residents are willing to maintain the integrity of their natural surroundings. This collaborative approach alludes to the potential for successful carbon projects that protect the vitality of the forested landscape and sustainable, rural livelihoods.

REFERENCES

Aryal, D. R., Morales-Ruiz, D. E., López-Cruz, S., Tondopó-Marroquín, C. N., Lara-Nucamendi, A., Jiménez-Trujillo, J. A., Pérez-Sánchez, E., Betanzos-Simon, J. E., Casasola-Coto, F., Martínez-Salinas, A., Sepúlveda-López, C. J., Ramírez-Díaz, R., La O Arias, M. A., Guevara-Hernández, F., Pinto-Ruiz, R., & Ibrahim, M. (2022). Silvopastoral systems and remnant forests enhance carbon storage in livestock-dominated landscapes in Mexico. *Scientific Reports*, *12*(1), 16769. https://doi.org/10.1038/s41598-022-21089-4

BC Ministry of Finance. (2023). *2023 British Columbia Financial and Economic Review* (No. 83rd Edition).

BC Parks. (2024). *Summary of Protected Area Designations and Allowable* [Types of parks and protected areas]. BC Parks. https://bcparks.ca/about/our-mission-responsibilities/types-parks-protected-areas/

Bernard, E., Penna, L. A. O., & Araújo, E. (2014). Downgrading, Downsizing, Degazettement, and Reclassification of Protected Areas in Brazil. *Conservation Biology*, *28*(4), 939–950. https://doi.org/10.1111/cobi.12298

Bogetti, J. (2024). *At risk or dismissed? Making the case for designated species at risk legislation in British Columbia* [Master of Science Thesis]. Thompson Rivers University.

Brcko, G. (2025, February 4). *Carbon Sequestration in Upper Clearwater Valley* [Microsoft Teams].

Briggs, T., & Eakins, I. (2024). *Environmental Ethics*. Wells Gray Adventures. https://www.skihike.com/about-us/environmental-ethics/

British Columbia Government. (2024, March 14). Park additions boost outdoor recreation, strengthen ecosystem protection [BC Gov News]. *Environment and Parks*. https://news.gov.bc.ca/releases/2024ENV0013-000343#:~:text=Newly%20introduced%20legislation%20will%20expand,opportunities%20for%20people%20to%C2%A0access%C2%A0outdoor%20recreation

Canadian Council of Forest Minister. (n.d.). *CRITERIA AND INDICATORS FRAMEWORK 2005*. The Canadian Council of Forest Ministers.

Canadian Council of Forest Ministers. (2022). *The Canadian Council of Forest Ministers' framework of Criteria and Indicators of Sustainable Forest Management in Canada—Canadian Council of Forest Ministers (CCFM)*. Canadian Council of Forest Ministers (CCFM). https://www.ccfm.org/releases/framework-of-criteria-and-indicators-of-sustainable-forest-management-in-canada/

Canadian interagency Forest Fire Center. (2025). *FireSmart BC*. https://firesmartbc.ca/

Carrie Moffatt. (2020, December). Barriers to Climate Action in Municipalities. *BarTalk British Columbia*. https://bartalk.org/article/features/2020-12/barriers-to-climate-action-in-municipalities

Clean BC. (2025). *B.C. OBPS PROGRAM AND REPORTING GUIDANCE* (Province of BC Climate Change). https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/obps/guidance/bc_obps_guidance.pdf

Cline, A. (2024, November 7). BC Forestry and Forest Carbon Offset Protocol [BRIGHTSPOT]. *Climate Library*. https://brightspot.co/library/bc-forestry-and-forest-carbon-offset-protocol/

Council of Canadian Academies. (2022). *Building a Resilient Canada*. The Expert Panel on Disaster Resilience in a Changing Climate. https://cca-reports.ca/wp-content/uploads/2022/01/Building-a-Resilient-Canada-web-EN.pdf

Davison, T. (2023). *Top Things To Do in Wells Gray Provincial Park and Clearwater*. Land of Hidden Waters. https://landofhiddenwaters.com/things-to-do/wells-gray-clearwater/

Destination British Columbia. (2025, Spring). *TOURISM IN BC*. https://www.destinationbc.ca/content/uploads/2025/03/Destination-BC-Value-of-Tourism-Spring-2025.pdf

Dunkelman, A. (2025, April 7). Canada's Carbon Markets: A Patchwork of Pricing Systems. *ClearBlue Markets*. https://www.clearbluemarkets.com/knowledge-base/canadas-carbon-markets-a-patchwork-of-pricing-systems

Environment and Climate Change Canada. (2024). *Protecting nature in British Columbia and across Canada to help fight climate change and protect biodiversity*. Government of Canada. https://www.canada.ca/en/environment-climate-change/news/2024/07/protecting-nature-in-british-columbia-and-across-canada-to-help-fight-climate-change-and-protect-biodiversity.html

Government of British Columbia. (2025a). *Modernizing Land Use Planning in British Columbia*. Land Use Planning. https://www2.gov.bc.ca/gov/content/industry/crown-land-water/land-use-planning/modernizing-land-use-planning

Government of British Columbia. (2025b, May 14). *Forest landscape plans*. Forest Stewardship. https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-landscape-plans?

Government of Canada. (2016). *2016 Census—Clearwater, District municipality* [Census Profile]. Statcan.gc.ca. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=CSD&Code1=5933067&Geo2=PR&Code2=59&SearchText=Clearwater&SearchType=Begins&SearchPR=01&B1=All&TABID=1&type=0

Government of Canada. (2025, February 18). *Canada 365: Welcoming the World. Every Day. The Federal Tourism Growth Strategy*. Business and Industry. https://ised-isde.canada.ca/site/canadian-tourism-sector/en/canada-365-welcoming-world-every-day-federal-tourism-growth-strategy

Gulbrandsen, L. H., & Wettestad, J. (2022). Carbon Pricing Under Pressure: Withering Markets? *Politics and Governance*, *10*(1), 230–234. https://doi.org/10.17645/pag.v10i1.5437

Habitat Conservation Trust Foundation. (2025). *Land Stewardship Grants*. https://hctf.ca/grants/conservation-lands-om/

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., Lovejoy, T. E., Sexton, J. O., Austin, M. P., Collins, C. D., Cook, W. M., Damschen, E. I., Ewers, R. M., Foster, B. L., Jenkins, C. N., King, A. J., Laurance, W. F., Levey, D. J., Margules, C. R., … Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, *1*(2), e1500052. https://doi.org/10.1126/sciadv.1500052

Interior Whitewater Expeditions. (2025). *Interior Whitewater Expeditions*. Interior Whitewater Expeditions. https://www.interiorwhitewater.com/

Kleinman, J. S., Goode, J. D., Fries, A. C., & Hart, J. L. (2019). Ecological consequences of compound disturbances in forest ecosystems: A systematic review. *Ecosphere*, *10*(11), e02962. https://doi.org/10.1002/ecs2.2962

Li, J., Zhang, X., Gu, Q., Zhang, Z., Wang, K., & Xu, Z. (2024). Spatiotemporal response of ecosystem services to tourism activities in urban forests. *Frontiers in Forests and Global Change*, *7*, 1361101. https://doi.org/10.3389/ffgc.2024.1361101

McAfee, B. J. & Canadian Forest Service (Eds.). (2008). *Implementing Ecosystem-based Management Approaches in Canada's Forests: A science-based policy dialogue*. Canadian Forest Service, Science and Programs Branch.

Ministry of Agriculture and Food. (2022, July 15). *The Extreme Weather Preparedness for Agriculture program*. British Columbia News; 2022AF0048-001116. https://archive.news.gov.bc.ca/releases/news_releases_2020-2024/2022AF0048-001116.htm?

Mota-Nieto, J., & García-Meneses, P. M. (2024). A stakeholder-centred narrative exploration on carbon capture, utilisation and storage: A systems thinking and participatory approach. *Energy Research & Social Science*, *113*, 103563. https://doi.org/10.1016/j.erss.2024.103563

Pais, S., Aquilué, N., Campos, J., Sil, Â., Marcos, B., Martínez-Freiría, F., Domínguez, J., Brotons, L., Honrado, J. P., & Regos, A. (2020). Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration. *Ecosystem Services*, *44*, 101143. https://doi.org/10.1016/j.ecoser.2020.101143

Patino, M. (2025). *ECOSYSTEM PRINCIPLES FOR BRITISH COLUMBIA PROTECTED AREAS: STRATEGIC PLANNING AND DECISION-MAKING IN WELLS GRAY PROVINCIAL PARK* [Master of Science Thesis]. Thompson Rivers University.

Province of British Columbia. (2025). *Present Land Use (1992-1997)—Colour Themed* [Map]. DataBC.

Province of British Columbia, Together for Wildlife Action 10 Team, Ministry of Water, Lands, and Resource Stewardship, & Ministry of Forests. (2023). *Together for Wildlife—Action 10: Spatial Analysis of Disturbance within Habitat Designations in British Columbia* (No. FREP Report #45). Province of British Columbia. https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/wildlife-wildlife-habitat/together-for-wildlife/t4w-action10-report.pdf

Santos-Martín, F., Martín-López, B., García-Llorente, M., Aguado, M., Benayas, J., & Montes, C. (2013). Unraveling the Relationships between Ecosystems and Human Wellbeing in Spain. *PLoS ONE*, *8*(9), e73249. https://doi.org/10.1371/journal.pone.0073249

Smyth, C., Metsaranta, J., Fortin, M., Le Noble, S., MacDonald, H., Wolfe, J., Boisvenue, C., Laganière, J., Krakowski, J., Zhu, K., Pare, D., Tompalsk, P., Emilson, E. J. S., Webster, K., Dosanjh, M., Venier, L., & Edwards, J. (2023). *2023 Blueprint for Forest Carbon Science in Canada* (Canadian Forest Service, p. 50). Natural Resources Canada. https://ostr-backend-prod.azurewebsites.net/server/api/core/bitstreams/2d5ac1e5-9320-470c-af81-542002cf1e3e/content

Thompson-Nicola Conservation Collaborative. (2024). *Conservation Action Plan for the Thompson Watershed* (No. June 2024; p. 140). Thompson-Nicola Conservation Collaborative. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://tnccollaborative.org/wp-content/uploads/2024/07/TNCC-Conservation-Action-Plan_June-2024-print.pdf

UNIFOR. (2024, April). *SUSTAINABLE HUMAN*. https://www.unifor.org/sites/default/files/documents/BRIEF_Future%20of%20Forests_UniforQu%C3%A9bec%20%28april%202024%29.pdf

Van Kooten, G. C., Bogle, T. N., & De Vries, F. P. (2015). Forest Carbon Offsets Revisited: Shedding Light on Darkwoods. *Forest Science*, *61*(2), 370–380. https://doi.org/10.5849/forsci.13-183

Verified Standard Carbon. (2020). *CANADIAN FOREST CARBON OFFSET METHODOLOGY* (VCS Methodology No. VM0034; Sectoral Scope 14). https://verra.org/wp-content/uploads/VM0034-Canadian-Forest-Carbon-Offset-Methodology-v2.0.pdf

Wells Gray Community Forest. (2023). Wells Gray Community Forest. https://www.wgcfc.ca/

Chapter 3. The Ecological Value of Forest Carbon

INTRODUCTION

In Canada, appropriate forest adaptation and mitigation practices have been identified as an essential part of the toolkit that will enhance the resilience and sustainability of Canadian forests (Antwi et al., 2023). Still, Mina et al. (2022) argue that current forest management strategies fail to effectively mitigate and adapt to current and projected climate change scenarios. These shortcomings carry important implications for the delivery of ecosystem services. In particular, they affect services that regulate microclimate and the concentration of greenhouse gases in the atmosphere, both of which play a critical role in maintaining the carbon balance in Canadian forests (Environment and Climate Change Canada, 2024b).

Previous studies reported increases in live biomass carbon stocks in temperate and boreal biomes during the first two decades of the 21st century (Yang et al., 2023). More recent findings suggest a shift. Li et al. (2025) observed a reversal of this trend from 2016 to 2022, with total live biomass carbon shifting from an increasing trend to a decreasing trend. In addition to these global-scale observations, regional research has shown that under many climate change scenarios, BC’s forests could become sources of greenhouse gas emissions, posing a significant risk to the province’s carbon balance (Gifford et al., 2022).

To conserve ecosystem services, and particularly to maximize forest carbon sequestration, it is imperative to manage enough forest and take action to make it a functional habitat network (Boudewyn et al., 2007). In regions with intensive cropping systems for the production of wood biomass, the provision of other ecosystem services becomes limited (Bubnicki et al., 2024). Consequently, there is a need to identify, assess, and map remnant natural forest patches with high capacity for ecosystem services provision. Typically, high conservation value forest patches harbour native tree species, have a long history of forest continuity, vertical and horizontal structural complexity, and low levels of anthropogenic influence

(Munteanu et al., 2022). The identification of remaining forests with natural structures and processes across landscapes and large regions is a key objective.

In regions like the Upper Clearwater Valley, the coexistence and partial connectivity between old-growth forests within protected areas and mid-successional forests on privately managed lands enable the expansion and continuity of key ecosystem services beyond formal conservation boundaries. Forest patches stewarded by Thompson Rivers University, Edgewood Blue, and The Land Conservancy are vital to maintain ecological connectivity with Wells Gray Provincial Park. They are critical to regional climate resilience and biodiversity conservation. In landscapes characterized by mixed land use, forest corridors are essential for sustaining carbon dynamics; an imperative that grows more urgent in the face of accelerating climate change. Quantifying carbon storage and sequestration is fundamental to identifying locally grounded mitigation strategies.

I assert that the Upper Clearwater Valley possesses exceptional carbon storage and sequestration capacity, strengthened by conservation-oriented land management and its ecological linkage to the protected area. This study aims to demonstrate that these forests store carbon at levels comparable to those in adjacent protected areas and have the potential to offset greenhouse gas emissions generated by valley residents. This underscores their value in local climate adaptation and mitigation efforts.

To prove this thesis, this chapter presents a high-resolution assessment of carbon storage and sequestration potential in the two areas that constitute the privately protected forests of the Valley: the western area (Edgewood Blue, and The Land Conservancy properties), and the eastern area (Thompson Rivers University lands). The estimation used a multi-stage methodology that integrates field-based measurements, remote sensing, and machine learning to generate precise forest carbon estimates. Ground data on forest structure were used to train models, which were scaled using LiDAR (Light Detection and Ranging)-derived metrics to estimate tree volume and crown features. A regression model predicted tree diameter at breast height (DBH), while a Random Forest classifier, enhanced with topographic variables, enabled species-level identification. Biomass calculations were performed using species-specific allometric equations, and final carbon estimates were derived through the i-Tree Eco software (Nowak & US Forest Service, 2021).

RESULTS

Species Classification Model

Two different Random Forest models for species classification were run for each of the two subareas that encompass the study area (Figure 1.2) due to its spatial discontinuity caused by the road. Both models revealed distinctly different levels of predictive performance between the two sides of the Upper Clearwater Valley. Appendix B summarizes the field data used for model training. Table 3.1 presents the key results of these models using the final validation data, including out-of-bag error, balanced accuracy, and the decision trees' parameters used for the western and eastern areas.

Model performance variables	**Western side**	**Eastern side**
Balanced accuracy	49.61%	57.85%
Out-Of-Bag prediction error	53.85%	36.59%
Number of decision trees	1000	500
Sample training data size	247	205
No. independent variables	5	6
Mtry	5	2

Table 3.1 Machine learning biomass model results from the validation data for the study area

The Random Forest models yielded different levels of predictive performance for the western and eastern sides of the study area. Despite the availability of an identical set of predictor variables for both models, the algorithm identified fundamentally different drivers of biomass across the two areas. The model for the eastern side, with a low Out-of-Bag (OOB) error of 36.59% and a balanced accuracy of 57.85%, in stark contrast to the western side, which exhibited a high OOB error of 53.85% and a near-chance balanced accuracy of 49.61%. The OOB represents a built-in validation method in the model that uses the training data itself to estimate model performance without needing a separate validation set, while the balanced accuracy is the average of sensitivity obtained on each class. This means that on the eastern side, the model misclassifies approximately 36.6% of samples during training, and across all tree species, the model correctly classifies 57.85% of cases on average. In contrast, in the western area, the model misclassifies over half the samples, resulting in lower accuracy in tree species classification. Tables 3.2 and 3.3. present the confusion matrices that illustrate the performance of both models through an overview of misclassifications.

Observed Predicted	Trembl. aspen	White birch	Western cedar	Cottonwood	Subalp. fir	Western hemlock	Lodge. pine	White spruce
Trembling aspen	26	0	0	1	2	4	1	4
White birch	3	40	2	6	1	3	4	2
Western red cedar	2	1	33	0	6	0	0	1
Black cottonwood	1	0	0	4	0	2	0	1
Subalpine fir	1	1	1	0	10	0	2	2
Western hemlock	2	2	0	3	0	8	1	6
Lodgepole pine	1	4	0	1	1	0	11	1
White spruce	5	1	0	0	2	5	1	12

Table 3.2 Confusion matrix of the species classification model in the eastern area of the study site

Observed Predicted	Trembl. aspen	White birch	Western cedar	Cottonwood	Subalp. fir	Western hemlock	Lodge. pine	White spruce
Trembling aspen	21	6	0	0	9	0	2	2
White birch	4	21	0	2	4	0	2	5
Western red cedar	0	0	7	1	0	0	0	0
Black cottonwood	3	0	1	7	0	0	0	0
Subalpine fir	4	3	0	1	9	1	0	12
Western hemlock	0	0	0	0	0	3	0	3
Lodgepole pine	0	1	0	0	0	0	0	0
White spruce	8	8	0	1	32	9	4	86

Table 3.3. Confusion matrix of the species classification model in the western area of the study site

The confusion matrix (Table 3.2) elucidates the class-wise performance behind the eastern model's overall balanced accuracy of 57.85%. Performance varies considerably across tree species, reflecting the model's ability to distinguish certain classes more reliably than others. The model demonstrates clear predictive skill but is constrained by significant inter-class confusion, particularly within two apparent groups: 1) the hardwood species Aspen-Cottonwood, and 2) the conifer species Spruce-Hemlock-Fir-Cedar. The high OOB error (36.59%) originates largely from this persistent confusion between morphologically similar species, rather than from a uniform failure across all classes. The confusion matrix for the western side (Table 3.3) reveals the model exhibits two critical failure modes: class imbalance domination and widespread, non-systematic confusion. It shows random misclassification where most species are regularly mistaken for the dominant spruce, while low-abundance species such as pine and hemlock are rarely predicted, generating essentially random predictions for other species. This is the hallmark of a model that has failed to learn meaningful feature-class relationships.

The variable importance analysis underscores a key ecological finding: the factors controlling species classification are not uniform across the valley. For the western side, species prediction was dominated almost exclusively by DBH and height metrics (Refer to Appendix C where variables of importance are ranked). Notably, from the fifteen available LiDAR-derived height categories representing the vertical distribution of the canopy, the model found that only five were significant for prediction. This suggests a complex forest structure. In opposition, the eastern model leveraged more diverse and complex predictors. Here, DBH was joined by multiple height metrics (including max height and 95th percentile height) and several topographic variables like channel base, valley depth, and openness. This indicates that forest biomass is influenced by a relationship between forest structure and topography on the eastern slope.

The optimized model configurations for each study area side reveal fundamentally distinct data structures and ecological predictability. The contrast is particularly observable in the model tuning. The poorly performing western model was the product of the most optimized tree decision using mtry = 5, meaning the algorithm was allowed to consider all five predictor variables at every node split. Despite this, the variable importance analysis identified only DBH and four height variables as meaningful contributors. This suggests that the predictive signal within the Western data is sparse and resides almost entirely in these two direct structural metrics. Conversely, the more effective eastern model was run with a restrictive mtry = 2. This setting forced each tree to be built using a small, random subset of variables, thereby enhancing decorrelation among trees and compelling the algorithm to identify the most robust and consistent predictors. The model successfully isolated six influential variables from the same initial suite, capturing key interactions between structural (e.g., canopy metrics) and topographic (e.g., elevation, slope) drivers.

Furthermore, this tuning difference aligns with the other optimized parameters: the western model required a larger ensemble (1000 trees) to stabilize its inherently noisy predictions, while the eastern model achieved stability with fewer trees (500). Even though a larger training sample was used for the western area (247 vs. 205), it was insufficient to overcome the complex relationships between the variables available.

Biomass Estimation

The LiDAR data processing and the biomass model estimated that there are 32,307 trees in the study area based on canopy structure. Based on the species classification model, there are 10,826 trees in the eastern area (57,85% accurate), and 21,481 trees in the western area (49,61% accurate). The species relative abundance for both sides of the study area is presented in Figure 3.1.

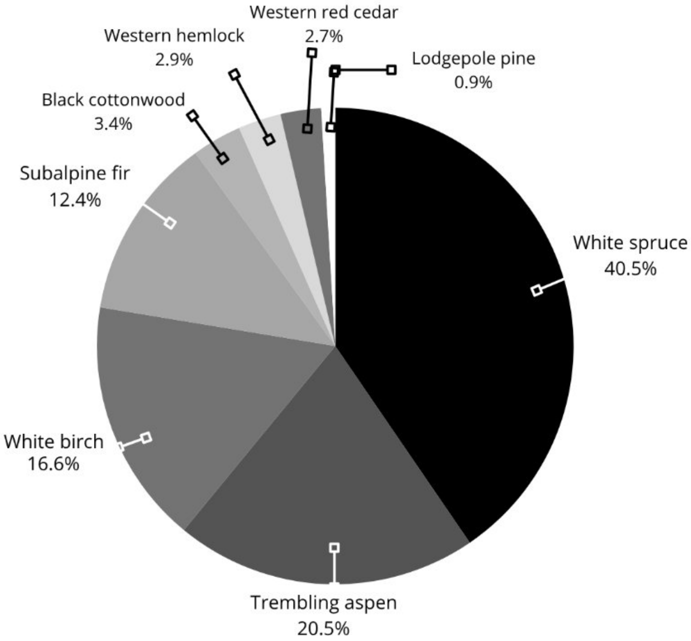


Figure 3.1 Tree species relative abundance in the total study area based on the biomass model

White spruce is the most abundant species with 13,068 stems. It is the foundational species of the study area’s forest in terms of population, constituting 40.5% of all trees counted. The following associated species were trembling aspen and white birch. Together with white spruce, these three species make up 77.6% of the total tree population. Lastly, black cottonwood, western hemlock, western red cedar, and lodgepole pine are relatively rare in this particular forest, comprising less than 3.4% of the total abundance. To examine the distribution of tree diversity and abundance in the field data, please refer to Appendix B.

Based on the species classification model, evergreen coniferous forest dominates the study area's vegetative cover in abundance and the leaf area, but mixed deciduous tree species also exist. This forest composition corresponds to most low to medium-elevation forests of the Central Interior Ecoprovince. White spruce and subalpine fir join lodgepole pine as the dominant conifers over much of the moister southern half of the Interior Plateau (Klinkenberg, 2023). Nevertheless, old-growth forests in the region are dominated by western hemlock and western redcedar, while vegetation is relatively diverse, and deciduous forests are increasing towards the northeast (Demarchi, 2011).

Regarding the deciduous tree species, the occurrence of stands of trembling aspen and paper birch indicates finer soil materials (Demarchi, 2011), while black cottonwood is characteristic of past fluvial processes, since it regenerates well after floods, channel migration, or other disturbances that expose bare mineral soil (Hood & Naiman, 2000). Figure 3.2 exhibits the relative abundance of tree species on each side of the study area to identify any differences in the composition of forest species between the two sides of the area.

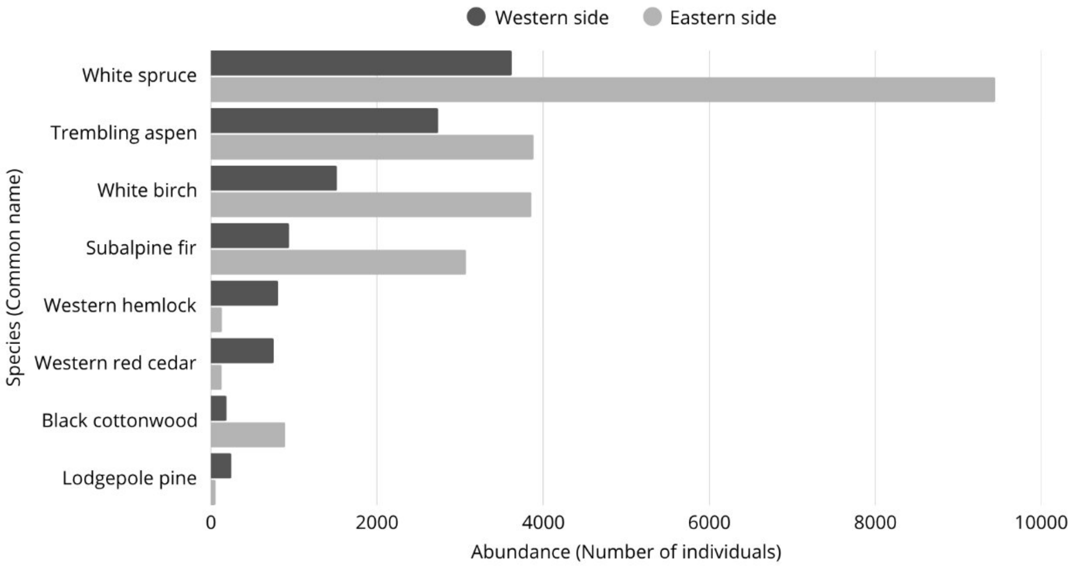


Figure 3.2 Tree species abundance on each side of the study area based on the biomass model

The white birch is the dominant species on both sides of the study area. The higher occurrence of the subalpine fir (3,073 trees) and trembling aspen in the western area versus the presence of western hemlock (811 trees) and western red cedar (757 trees) in the eastern area suggests that each forest side is at a different successional stage.

Carbon Stock and Sequestration Model

The carbon stock estimation for the study area, in terms of the carbon storage per species estimated, is shown in Figure 3.3.

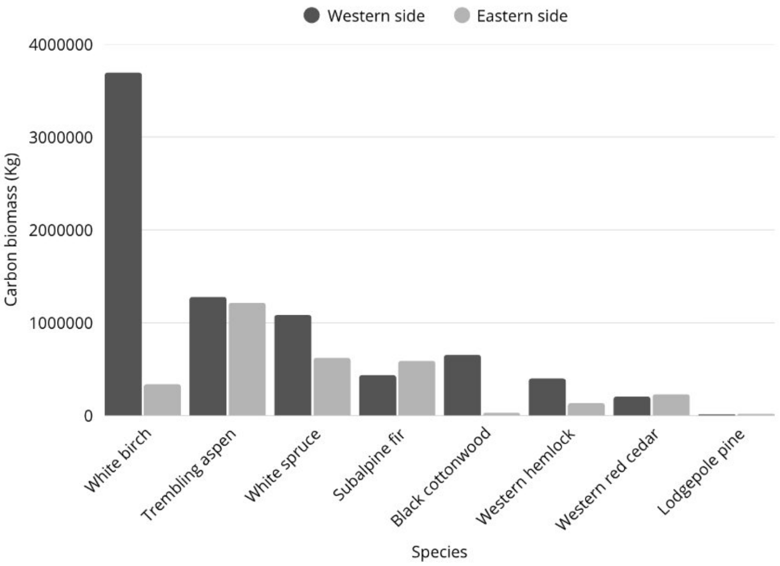


Figure 3.3 Carbon storage of the study area calculated using Natural Resources Canada's biomass calculator variables based on LiDAR and field data for the individual tree structure measurements.

Figure 3.3. indicated a representative difference in the storage capacity of each side of the valley due to its size. Nevertheless, the major contributors to the carbon stock for both sides did not correspond precisely to the most dominant species in the biomass model, but to the most abundant deciduous tree species, followed by the dominant white spruce (Figure 3.1). In total, the eastern area (44 ha) stores 3,175,750 kg of C, while the western area (81 ha) stores 7,758,582 kg of C, for a total of 10,934,332 kg of C (12,053 tonnes of C) currently stored in the modelled forest. Considering both polygons' areas, the carbon stocks are 72,176 kg C/ha and 95,785 kg C/ha, achieving an average of 87,474 kg C/ha for the entire study area. Figure 3.8 presents the above-ground and below-ground biomass for carbon storage. Figure 3.8 indicates a disparity in total carbon storage between the two regions, with the western side supporting a substantially greater total biomass (11 times greater) than the eastern side due to its larger size. The single largest biomass pool species is paper birch on the western side (~3.69 million kg), making it a key species for carbon storage in the study area. This is followed by trembling aspen and white spruce, which are major contributors on both sides. Figure 3.4 presents the carbon storage per area (kg/ha) to estimate carbon stocks comparable to literature findings in other locations or those resulting from national-scale models.

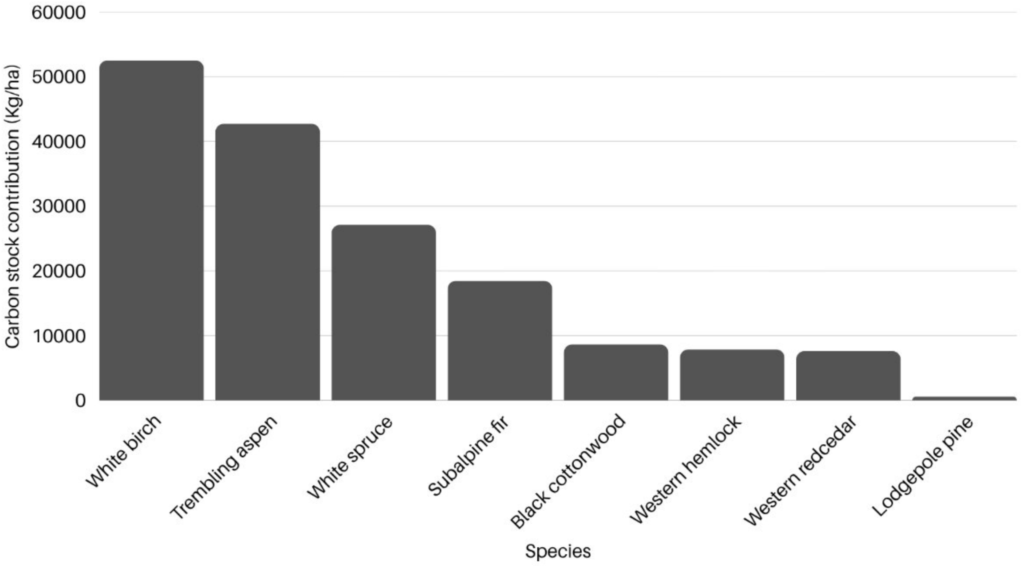


Figure 3.4 Carbon stock given in biomass per area of the private forests in the Upper Clearwater Valley

According to Figure 3.4, paper birch and black cottonwood exhibit a strong western-side preference, with their biomass on the west being an order of magnitude greater than on the east. While subalpine fir demonstrates a reverse trend, which constitutes a larger carbon pool on the eastern side than on the western side. Finally, lodgepole pine, western hemlock, and western red cedar represent smaller components of the total carbon budget in this study area, with their biomass relatively balanced between the two sides.

Carbon sequestration capacity was estimated using the allometric equations of each tree species’ growth and decomposition rates through the i-Tree Eco Tool. Figure 3.5 indicates the forest's annual carbon sequestration rate from both sides of the study area, calculated from the carbon stocks, growth rates and decomposition rates described in Chapter 2.

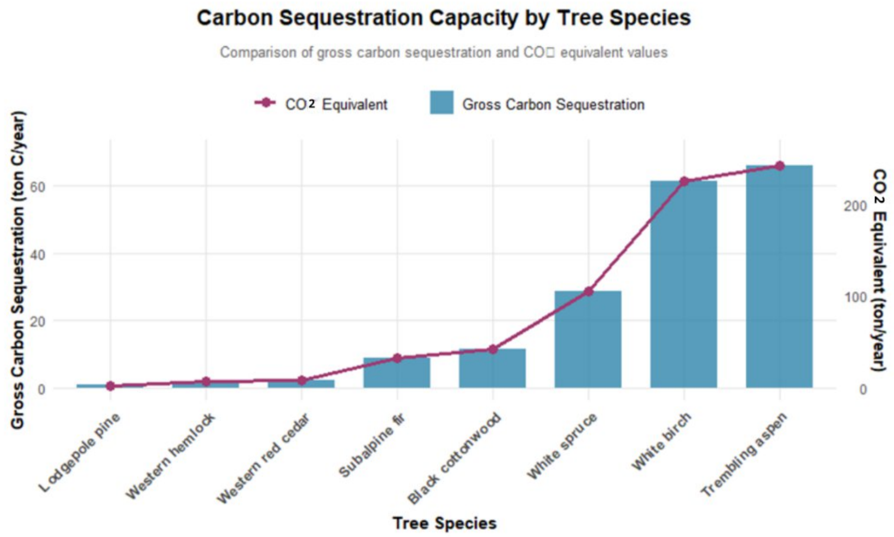


Figure 3.5 Annual carbon sequestration of the forest in the study area calculated by the i-Tree Eco Tool (2025)

The privately protected Upper Clearwater Valley forest sequesters 181.17 metric tonnes of carbon annually. Trembling aspen demonstrated the highest carbon sequestration capacity (65.95 t C/yr), followed closely by white birch (61.31 t C/yr). These two species sequestered substantially more carbon than the others, with values for white spruce (28.73 t C/yr) being less than half that of the largest contributors. White spruce and subalpine fir were the third and fourth contributors to annual gross carbon sequestration, respectively. Those results can be mainly attributed to their relatively large abundance in the study area, rather than their carbon sequestration capacity. Coniferous species, particularly lodgepole pine (0.89 t C/yr), western hemlock, and western red cedar, exhibited the lowest sequestration rates. This hierarchy was consistent when expressed in CO_2 equivalents, confirming the dominance of deciduous broadleaf species in carbon capture in this ecosystem.

Ground cover spatial analysis of the study area

To analyze the spatial context of carbon stocks in the study area, it is essential to decide which zones could hold the greatest potential to increase carbon stocks based on at least some of the factors mentioned previously. For that purpose, a good starting point is to analyze the current land cover composition of the Upper Clearwater Valley around the privately protected forest and then determine how much area could potentially be used for carbon enhancement. Table 3.4 presents Land cover percentage distribution in Upper Clearwater Valley taken from Esri Sentinel-2 Land Cover Explorer.

Land cover	**Upper Clearwater Valley Area (m^2)**	**Private lands in the Valley Area (m^2)**	**Privately-owned Percentage**
Water	255,727.32	66,310.80	25.93%
Trees	44,755,886.47	16,661,040.37	37.22%
Crops	71,719.84	71,719.84	100%
Built area	852,925.23	841,606.31	98.67%
Bare ground	42,771.47	33,956.74	79.39%
Rangeland	4,287,564.46	3,881,085.24	90.51%

Table 3.4 Land cover percentage distribution in Upper Clearwater Valley. Land cover layers taken from Esri Sentinel-2 Land Cover Explorer

Table 3.4 presents the distribution of major land cover classes within the Upper Clearwater Valley and, critically, quantifies the proportion of each class under private ownership. The dominant land cover is forest ('Trees'), covering 44.76 km² (over 90% of the total non-water area). However, only 37.22% of this forested land is privately held. This indicates that while forest is the valley's primary ecosystem, a majority of it falls under public or other tenure, focusing the relevance of private conservation strategies on a specific, minority portion of the total forest resource. Conversely, anthropogenic land covers are mostly privately controlled. Nearly all Cropland (100%), Built Area (98.67%), and Rangeland (90.51%) are on private lands. This creates a distinct landscape mosaic where private parcels consist of a mix of forest fragments embedded within a matrix of agriculture, settlement, and grazing land. The high private share of Bare Ground (79.39%) likely relates to agricultural or developmental activities.

To understand this ground cover dynamic visually, Figure 3.6 presents the current land cover categorization map of the Upper Clearwater Valley around the study area.

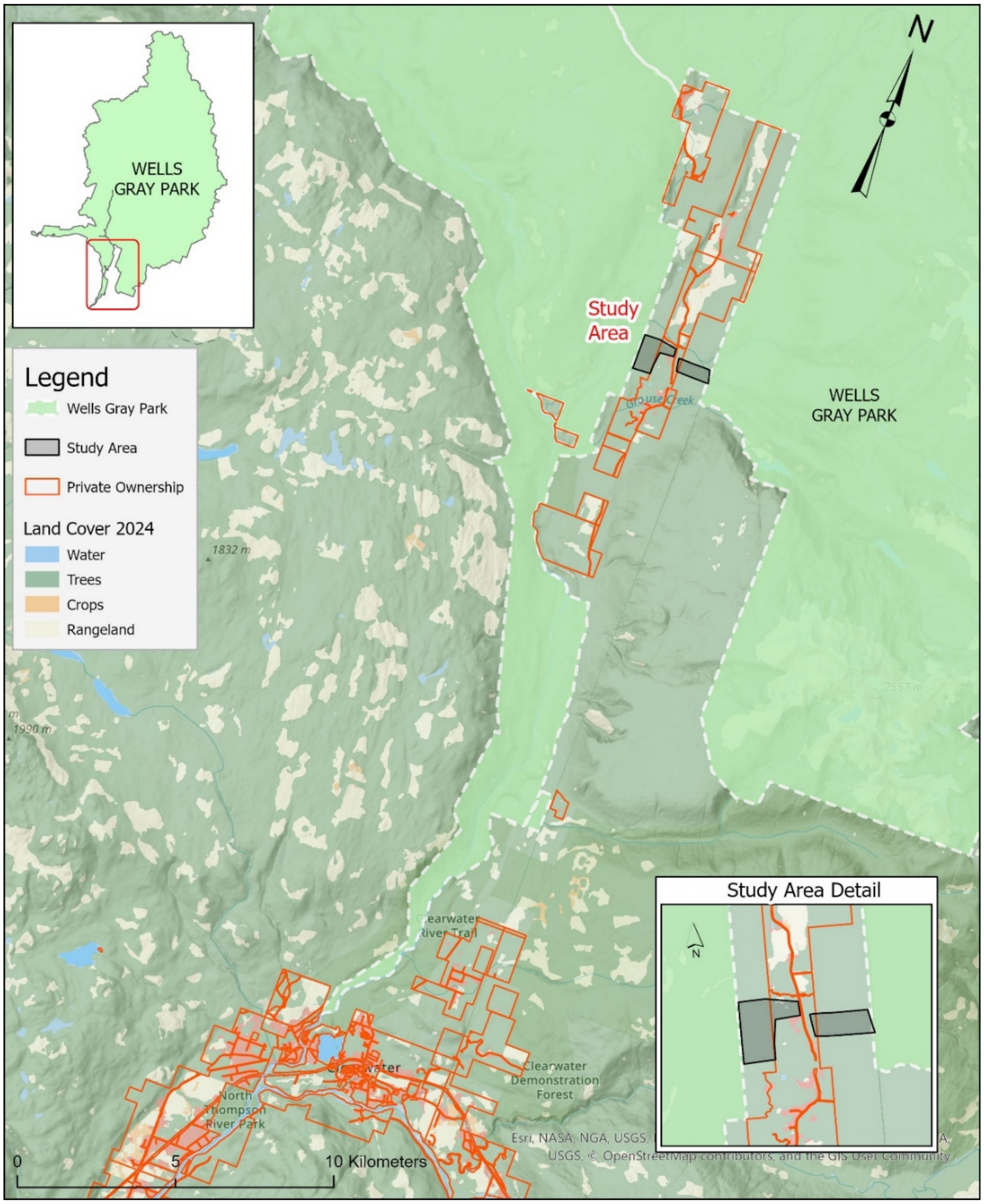


Figure 3.6 Land use distribution in the Upper Clearwater Valley. Land cover layers taken from Esri Sentinel-2 Land Cover Explorer

DISCUSSION

Model Prediction Assessment

To effectively target strategic conservation areas, it is crucial to use reliable local sources that capture detailed structural information. Most studies have relied on global or continental models for local decision-making, leading to misinterpretations in conservation efforts due to the inadequate identification of forest structure. Despite high predictive power, these broad-scale reference maps often disagree and fail to align with higher-quality biomass maps produced at smaller scales (Ploton et al., 2020). Large-scale models typically rely on limited, clustered data, which can misrepresent local features (Meyer et al., 2019). This lack of actionable maps hinders the development of effective national climate and biodiversity strategies (Bubnicki et al., 2024). Consequently, local modelling, which captures specific details at finer than 250 m scales, has become more prevalent due to the availability of extensive spatial datasets with high resolution (Sothe et al., 2022).

The primary objective of this thesis chapter was to develop a high-resolution, local-scale model for predicting forest biomass as a proxy for conservation value. The resulting models achieved moderate accuracies of 49.61% and 57.85% for the western and eastern areas, respectively. A critical examination of this performance, contextualized within existing literature, reveals fundamental insights into the data requirements and ecological complexity of such predictive tasks. For local modelling, spatially continuous datasets of ecosystem variables are needed to analyze the spatial patterns and dynamics. Ecological variables are typically acquired through field work, providing only data with a limited spatial extent, such as plot-based vegetation records (Meyer et al., 2019). This is where remote sensing and predictive modelling were valuable to derive spatially continuous datasets from limited field data. It can provide data over large areas at a fraction of the cost associated with extensive sampling, and enables access to inaccessible places (Kumar & Mutanga, 2017).

The carbon sequestration model presented relied exclusively on a small sample of field data, LiDAR-derived structural metrics (e.g., tree height, canopy complexity) and topography; with those components. Examples of such datasets include LiDAR-based forest structure measurements (Davies & Asner, 2014; Meyer et al., 2019) and high-spatial and thematic resolution land cover/land-use maps. Nevertheless, the use of these variables in the species classification model produced modest accuracy. This finding directly aligns with a body of literature suggesting that structural data alone may be insufficient for high-fidelity ecological prediction, particularly in diverse forests. While LiDAR metrics are powerfully correlated with biomass (Kumar & Mutanga, 2017), they struggle to differentiate species composition, a critical driver of carbon storage potential and ecosystem function.

This study's results reinforce the conclusion of Liu et al. (2022), who reported low estimation accuracy in complex, dense forests using limited data sources and advocated for integrated multi-source approaches. More importantly, the performance observed here underscores a key limitation highlighted in broader remote sensing ecology: LiDAR data alone struggles to predict species. Spectral information from multispectral or hyperspectral sensors is often necessary to distinguish species based on their unique photosynthetic and biochemical properties (Davies & Asner, 2014). The absence of such spectral data in our model likely limited its ability to resolve the specific species-driven allometric relationships and physiological traits that underpin biomass accumulation, explaining the sub-optimal accuracy. This aligns with the high-accuracy (80-90%) findings of Maesano et al. (2022) and Liu et al. (2022), who explicitly combined LiDAR structural data with multispectral imagery to achieve superior results.

The stark contrast in model drivers between the western area (biomass driven simply by tree size: DBH and height) and the eastern area (a complex interaction of size, canopy strata, and topography) is a central result. This heterogeneity validates the argument for local-scale modelling presented by Ploton et al. (2020) and Sothe et al. (2022). Continental or global models, which rely on generalized relationships, would fail to capture this landscape-scale complexity, leading to the misinterpretations they suggested. The eastern model's reliance on topographic complexity supports the findings of Bubnicki et al. (2024), who linked taller, more structurally diverse forests to complex topography. However, the western model's lack of such a relationship demonstrates that the terrain and tree assemblage characteristics on each side of the study area vary widely. This discrepancy powerfully illustrates how clustered data in large-scale models **(**Meyer et al., 2019) can generalize some critical local dynamics.

The model’s accuracy rates (49.61-57.85%) are lower than the 60-90% range reported by Chen et al. (2018) or the 68.87% from Hu et al. (2020). This accuracy is an indicator of poor model construction but a consequence of two factors. As discussed, both Chen et al. (2018) and Hu et al. (2020) incorporated texture and biophysical variables from satellite imagery (i.e., multispectral data), not just structure. The use of a LiDAR-only dataset is more limited in explanatory scope. Hu et al. (2020) correctly concluded that accuracy is dependent on specific ecological contexts. The topographically complex, mixed-wood forest in the study area presents a more complex prediction environment than more homogeneous plantations or forests, a challenge noted by Liu et al. (2022). The higher accuracy in our more complex eastern area, where the model could leverage topographic interactions, suggests that the algorithm performed robustly given the available data.

Although this study successfully implemented the local-scale machine-learning framework advocated by Meyer et al. (2019) and Sothe et al. (2022) to produce a high-resolution map where none existed, the literature points the way forward to higher accuracy. Following the integrated methodology of Maesano et al. (2022), future iterations must integrate multispectral data (e.g., Sentinel-2) with the already analyzed LiDAR-derived structure. This would directly address the species-classification limitation of LiDAR alone, allowing the model to capture the spectral signatures of different tree species.

The Ecological Importance of the Valley

The species classification and biomass model indicate a transition in subalpine mixed woods forest composition across the study area, from a structurally complex canopy in the east to a simpler one in the west. The higher abundance of fast-growing species like white spruce, trembling aspen, and white birch generally indicates forest growth after a wildfire disturbance. Shade-tolerant, long-lived species like western red cedar and western hemlock in the eastern area represent a more stable tree community with a long period without major disturbance since these latter species can germinate and grow in the understory (Assmuth et al., 2021). The western side has lower diversity and will likely evolve into a simpler structure dominated by white spruce, with shade-tolerant conifers like subalpine fir and hemlock with lower heights.

This trend reflects a pronounced environmental gradient. The western side is dominated by broadleaf species, suggesting drier, warmer conditions (Klinkenberg, 2023) and more recent disturbances consistent with mid-successional stages (Mitchell & Bullen, 2020). This favours drought- and fire-adapted species such as spruce and aspen. The eastern side is richer and moister, supporting late-successional species like cedar and hemlock (Klinkenberg, 2023). The increasing presence of subalpine fir in the east further signals a shift toward a more typical interior or subalpine coniferous forest community (Gifford et al., 2022).

The evidence from DBH distribution (Freund et al., 2015), and widespread aspen-dominance (Payne et al., 2019) indicates the development of early old-growth forest on both sides of the study area. This pattern reflects forest regeneration following wildfires that affected the lowlands of the southern Clearwater Valley in the early 20th century (Goward, 2024). This variation in the species compositions between the eastern and western sides of the study area underscores the need for targeted conservation efforts that reflect local biodiversity and carbon sequestration potential. Findings further support the ecological importance of maintaining diverse forest ecosystems, which promote more efficient canopy structures, enhance light capture, and increase primary productivity (Poorter et al., 2015). These factors contribute to greater carbon sequestration and help sustain forest resilience in the face of climate change and wildfire disturbances, both of which often alter species composition and ecosystem function (Assmuth et al., 2021; Liang et al., 2017).

Regarding carbon storage, the contribution of the highest abundances of trembling aspen (*P. tremuloides*), white birch (*B. papyrifera*), and white spruce (*P. glauca*) in the study area carries essential ecological implications. White birch, trembling aspen and white spruce are disturbance-related and represent a mid-successional stage in forest development. Early stages are generally aspen-dominated, and late stages are spruce-fir-birch dominated (Payne et al., 2019). White birch was the most significant contributor to the carbon stock, with 52 Mg C/ha (52,511 Kg/ha). Boudewyn et al. (2007) modelled the overstory biomass for the principal tree genus per ecozone, finding birch (*Betula* genus) stands could store around 49-78 Mg C/ha in the montane cordillera ecozone. Even though this result only accounts for the above-ground carbon stock compared to the total (above-ground and below-ground carbon stock) modelled by this research, the comparison provides a broad idea of the current capacity of the white birches in the Upper Clearwater Valley. Additionally, it is critical to highlight that white birch has been recognized as an initial booster of biomass and carbon inputs during stand renewal, optimizing carbon storage (Assmuth et al., 2021).

Trembling aspen contributed 42 Mg C/ha (42,720 kg/ha) to the local carbon stock. This species has been recognized as a key component of mixed wood stands, often supporting higher overall carbon stocks than pure conifer stands, reaching around 239 Mg C/ha for total stock in mature stands in the boreal forest (Payne et al., 2019). Meanwhile, white spruce contributed to the carbon stock with 27 Mg C/ha (21,099 kg/ha). This result is comparable with the findings of Boudewyn et al. (2007), who modelled that spruces in the montane cordillera can store between 2 and 191 Mg C/ha above-ground. From an ecological perspective, annual gross carbon sequestration rates are valuable indicators for assessing the physiological capacity of forest ecosystems to capture and store carbon (Cheung, 2024). In the context of policymaking and carbon market mechanisms, expressing sequestration in terms of carbon dioxide equivalent (CO_2e) provides a more precise and standardized metric for quantifying and commodifying carbon as a tradable environmental asset.

The Interior Cedar Hemlock - ICH biogeoclimatic (BEC) zone, and specifically, the southern ICH rainforest ecosystems, cover just under 5% of BC but contain over a tenth of the province's aboveground carbon hotspots (Demarchi, 2011; Gifford et al., 2022; Mitchell & Bullen, 2020). It has the third-highest density of aboveground carbon (91.47 Mg C/ha) among BC's BEC zones, and the eighth (241.6 Mg C/ha) and seventh (332.7 Mg C/ha) highest belowground and total carbon densities, respectively (Mitchell & Bullen, 2020). This model estimated a comparable total carbon density for the study area, equivalent to 165.48 Mg C/ha (165,486 kg/ha). It is essential to note that this model only considered forest carbon stocks driven by above-ground field data and below-ground carbon stock estimations based on the literature's allometric equations for the species found. In contrast, the models presented by Mitchell & Bullen (2020) included all the land covers in the southern ICH BEC zone.

To scale down the comparisons, Sothe et al. (2022) used a large number of field measurements, multisource satellite, climate and topographic data and a machine learning algorithm to produce the first wall-to-wall estimates of C stocks and uncertainties in plants and soils of Canada at 250 m spatial resolution. They estimated that the study area holds an average of 7.92 kg C/m^2 (79,2 Mg/ha) (value obtained masking this research study area in 75 pixels of their C stock model on QGIS). This research model estimated 16.5 kg C/m^2 (165.48 Mg C/ha). The larger value produced by this model compared to what was obtained by Soethe et al. (2022) underscores the importance of modelling at finer scales for extracting essential features of the landscape that larger-scale models cannot illustrate, as stated at the beginning of this section.

The carbon storage capacity of a forest is a complex function of its age, composition, and structure (Mitchell & Bullen, 2020). In the study area, where forests are approximately 100 years old due to post-wildfire regeneration, the current carbon stock can be contextualized using regional data. For instance, Hoover & Smith

(2023) report that trees in the 81–120-year age class in the United States Northern Rockies store an average of 56.7 Mg C/ha, while 61-80 years age class stores around 47.4 Mg C/ha. However, this stock is not uniform, as abiotic and biotic factors like climate and species composition further influence the quantity and distribution of carbon among different ecosystem pools (Springer et al., 2024). The significance of stand composition is highlighted by findings that mixed wood and broad-leaved stands often hold higher carbon stocks than pure coniferous stands (Payne et al., 2019). Since its potential increases over time if wildfire management is applied, the age of the protected forests in the valley is a critical factor when considering the area's importance for enhancing the local carbon cycle and ensuring the continuity of all regulating ecosystem services.

In the context of subalpine forests in Canada, understanding carbon sequestration rates and the importance of calculating carbon sequestration rather than merely carbon storage is imperative for effective forest management and climate mitigation strategies. The privately protected forest of the Upper Clearwater Valley sequesters 181.6 t C/yr (0.0008 Mt C/yr). Sharma et al. (2023) estimated the average amount of carbon sequestered annually from the atmosphere of all the national parks (5.6 million hectares) in Canada. They found that the net carbon sequestered was 2.4 Mt C/yr, with an annual loss of 11% due to plant respiration. The study area’s carbon sequestration rate, even though lower than the rate found for national parks, demonstrates the high value of the study area to mitigate local greenhouse gas emissions compared to more conserved, complex, and older forests protected in national parks.

Hoover & Smith (2023) found that carbon accumulation rates are a function of multiple factors, and vary across the age classes, with rates generally declining with age, but with values often peaking in mid-aged forests. To exemplify this phenomenon at a local scale, the overall average rate of carbon sequestration of forests located in the northern region of the Rocky Mountains of the United States for the youngest age class (0-5 years old stands) is 0.54 t C/ha/yr. It increases to 0.85 t C/ha/yr for the age class 21-40 years, and then starts diminishing to reach a net loss of carbon sequestration capacity for the age class 81-120 years with -0.25 t

C/ha/yr. It is essential to clarify that young trees can exhibit a higher carbon sequestration rate, but only if they are part of old forests, which often support a greater diversity of tree species and age classes, which leads to higher overall productivity and thus carbon sequestration (Jia & He, 2023; Springer et al., 2024). More complex forests tend to be more resilient against external stressors, such as drought or disease, which can impact carbon dynamics.

These contrasting findings reinforce the importance of conserving this forest to achieve a complex structure over time, to transition from mid-successional phases to early old-growth stages, which can enhance biodiversity and productivity while maximizing carbon storage. Research by Triviño et al. (2015) highlighted the importance of complex forest ecosystems as they store carbon and process it more efficiently, making them crucial players in the carbon cycle. Furthermore, forest carbon flux estimates are subject to substantial uncertainty due to changes in environmental conditions affecting net primary productivity and decomposition (e.g., climate change, CO_2 fertilization effect, nitrogen deposition), and a limited understanding of disturbance processes (Council of Canadian Academies, 2022a). Nevertheless, it is crucial to attribute a high ecological value for carbon sequestration to areas like the privately protected forest in the Upper Clearwater Valley. With its natural history, management practices, and strategic location, this forest frames a suitable scenario to enhance carbon capture and storage despite climate change threats.

To build on this understanding of local drivers, the ecological importance of this protected forest in the Upper Clearwater Valley extends to its role within regional carbon storage patterns. The southern Interior Cedar-Hemlock (ICH) zone exemplifies this as it stores 7.7% of the province's aboveground carbon on just 4.6% of its land area (Mitchell & Bullen, 2020). The Upper Clearwater Valley possesses a profound natural history that is directly responsible for its high carbon storage capacity. As asserted by Goward (2024), a renown lichenologist, the Caribou Mountains acted as a glacial refugium during the Pleistocene. This created a unique biogeographical region, which has endowed the area with an unusually rich vascular flora, with over 1,000 documented species and discoveries occurring annually. This indicates that its full ecological value might be larger than measured so far. Projections reveal that, by 2050, boreal, subalpine, and alpine ecosystems will decrease substantially as warmer, drier climate regimes expand (Gifford et al., 2022). This makes the valley’s forests a critical, and potentially shrinking, habitat for species adapted to cooler conditions.

It is crucial to understand how carbon sequestration allows for more effective forest management decisions. For instance, implementing silvicultural practices that enhance tree growth can lead to greater carbon uptake. This contrasts with merely assessing carbon storage, which may overlook operational strategies that could optimize carbon sequestration (Sharma et al., 2023). Since carbon sequestration estimation constantly changes, continuous assessment of carbon sequestration can identify how forests adapt to changing environmental conditions to enable strategies to enhance resilience and biodiversity (Cook-Patton et al., 2020). Governments, NGOs and carbon neutrality consultants often use carbon sequestration rates to set and evaluate climate policy. Accurate metrics of how much carbon is sequestered inform cap-and-trade systems and other regulatory measures to achieve climate targets (Cook-Patton et al., 2020).

The assessment of carbon storage and sequestration capacity in the protected forest studied in the upper Clearwater Valley revealed the ecosystem's capacity to respond to changes in climate and management practices. Under continuing ecological loss, such landscapes are paramount as a key conservation priority. Remnants of naturally dynamic forests like this one are key biodiversity hotspots, providing essential habitats and forming resilient ecosystems that deliver multiple services (Bubnicki et al., 2024). Their scarcity underscores the urgency of protection. This research provides spatially explicit evidence identifying the privately protected forests in the valley as a high conservation value forest. The valley’s location, bordered by Wells Gray Provincial Park, and its substantial post-wildfire carbon reserves position it as a stronghold for both biodiversity and carbon sequestration. The protection of these forests constitutes a strategic investment in an ecological reservoir that supports species persistence and contributes to long-term climate regulation.

Carbon Sequestration Enhancement Strategies

Enhancing carbon sequestration and stocks is important for climate change mitigation and maintaining biodiversity (Environment and Climate Change Canada, 2024b). A fundamental consideration is the distinction between the two components of forest carbon dynamics: the total carbon stock and the rate of carbon sequestration. Management actions do not affect these components uniformly and priorities may shift based on overarching goals, which can include wildlife habitat provision and sustainable timber production (Hoover & Smith, 2023). Consequently, strategies that maximize carbon storage, often achieved in older, uneven-aged stands with large trees, can differ from those designed to maximize sequestration rates or specific biodiversity outcomes (Springer et al., 2024).

Nature-based climate solutions focus on the maintenance and expansion of biomass to increase carbon stocks, rather than employing active soil or tree-thickening methods. These initiatives include reforestation, afforestation, and promoting natural regeneration through conservation. International estimates provide a sense of scale. Afforestation and reforestation globally can increase net carbon stocks by 2.8–5.5 Mt CO_2e/yr. While improved forest management contributes 0.2–1.2 Mt CO_2e/yr (Griscom et al., 2017). Such estimates provide an approximate range of the potential carbon sequestration benefits associated with these strategies (Canadian Council of Forest Ministers, 2022).

Afforestation and reforestation measures are central to many current large-scale, carbon-focused policy approaches, yet they are often based on monoculture plantations. Schirpke et al. (2017) discuss the impacts of changing land use due to reforestation and raise questions about the ecological benefits of monoculture plantations compared to diverse ecosystems, particularly under the pressures of climate change and economic development. Monoculture afforestation can significantly alter ecosystem services and negatively influence biodiversity conservation efforts (Andrews-Key & Nelson, 2025). The economic benefits of diverse forestry practices are higher than those of monoculture forestry, as greater diversity enhances both tourism and ecological services through biodiversity (Iversen et al., 2021).

Despite an established body of research, a broad-scale implementation of forest practices to address climate change impacts in Canada has been slow to advance (Andrews-Key & Nelson, 2025; Antwi et al., 2023). 27% of other practices, such as afforestation and reforestation, were classified as mainstream and in common use across several provinces (Antwi et al., 2023). The less common adaptation practices reported include nature-based solutions such as the designation of ecological corridors, the expansion of protected areas to improve climate resilience, and the creation of carbon offset projects through designated forest reserves (Canadian Council of Forest Ministers, 2022). Alternative options, such as natural regeneration of secondary forests, are more effective for on-site carbon storage (Feng et al., 2022) and biodiversity conservation (Schuldt et al., 2023). Reforestation is a key natural mitigation strategy that needs more focus on cost-effective opportunities. While it may involve trade-offs with other land uses and high establishment costs, to engage the private sector for initial commercial harvests can help reduce expenses and promote natural and assisted forest regeneration (Griscom et al., 2017).

The prevention of forest conversion to non-forested land through conservation is another critical strategy. Conservation preserves the ongoing capacity of forests to sequester carbon, even though sequestration rates in aboveground biomass typically decline as forests mature (Framstad et al., 2013). Natural regeneration in conserved areas avoids short-term CO_2e emissions, to align with objectives to protect old-growth forests, wildlife habitat, and other ecosystem services. For example, forest conversion to agricultural land in Canada in 2018 resulted in immediate emissions of 0.9 Mt CO_2e, with residual emissions from past conversions adding another 1.5 Mt CO_2e (Council of Canadian Academies, 2022a). While conservation keeps existing carbon stored in trees, it may not increase sequestration rates without complementary management, such as tree maintenance (Nowak et al., 2002c).

In this context, the private protected forests in the valley have been conserved, safeguarding their existing carbon stock. When one considers the mosaic of land uses in private parcels, to integrate the abovementioned practices could optimize carbon sequestration to help offset local greenhouse gas emissions. To combine conservation with low-intensity harvesting and agricultural practices can also enhance carbon stocks. Agroforestry systems, for instance, allow for simultaneous carbon sequestration while they provide food and other ecosystem services (Mina et al., 2022). As Ameray et al. (2021) highlighted, the integration of tree cover into agricultural landscapes can improve soil organic carbon levels, creating a multifaceted approach to land management.

The Effects of Wildfires on Carbon Stocks

The increasing threat of wildfires must also be considered in any carbon management plan. Wildfires have recently become a leading cause of carbon stock loss in BC. The area burned in 2017 and 2018 (each exceeding 1 million hectares) surpassed the previous recorded maximum of 0.82 million hectares in 1958 (Hanes et al., 2019). In the temperate forests of western North America, stand-replacing wildfires temporarily reduce aboveground carbon by combusting live and dead biomass and increasing decomposable dead wood (Kurz et al., 2013). While these areas typically recover aboveground carbon over the fire-free interval through tree re-establishment and biomass accumulation, more frequent fires disrupt this cycle (Cook-Patton et al., 2020; Jia & He, 2023; Smyth et al., 2020).

Nevertheless, increased fire activity also presents opportunities. Metsaranta et al. (2019) and Smyth et al. (2020) note that post-fire rehabilitation, such as replanting, can reduce future greenhouse gas emissions compared to reliance on natural regeneration alone. Replanting allows for the establishment of seedlings with genetic gain and increased climate resilience. In BC, Metsaranta et al. (2019) projected that cumulative net GHG benefits from rehabilitating about 14% of the burned area could range from –79 to −32 Mt CO_2e by 2070. However, these net reduction benefits are not realized for 23 to 31 years due to an initial "emissions debt" from harvesting wood products and residue management.

In summary, enhancing forest carbon in the Upper Clearwater Valley could use various strategies that balance sequestration rates with long-term stock stability and biodiversity conservation. This includes employing targeted silviculture to accelerate the development of the young stands, integrating agroforestry practices within the land-use mosaic, and implementing preventive fire-protection forestry practices and post-fire rehabilitation to mitigate carbon losses. Furthermore, the continuation of natural regeneration in some zones to leave the critical wildlife corridor intact has been a successful strategy. A comprehensive initial carbon assessment and acknowledgment of the inherent trade-offs must guide the prioritization of these strategies. Ultimately, by integrating these diverse management actions, the conserved forests of the Upper Clearwater Valley can maximize their contribution to climate mitigation while they continue to support biodiversity and sustainable land-use objectives.

Carbon Stocks in Private Protected Forests

The expansion of the forest to increase carbon stocks

Private forests are an integral part of landscapes and ecosystems. These forests are unfortunately often overlooked in broader conservation and carbon sequestration discussions, even though they play a critical role in climate change mitigation and contribute substantially to ecological balance. Effective management of these lands can enhance connectivity between forest patches, improving overall landscape carbon stocks. Increasing carbon stocks in private forests can reduce land degradation and deforestation pressures. Ter-Mikaelian et al. (2021) indicate that better management practices, which include longer rotation periods and reduced-impact logging, can transform private lands into more effective carbon sinks. With the promotion of biodiversity conservation within private woodlands, landowners contribute to carbon capture and the resilience of ecosystems, ultimately supporting overall forest health and longevity (Schuldt et al., 2023). To maintain rising carbon stocks in private forests offers other ecosystem services and economic benefits to landowners and local communities (Antwi et al., 2023). Enhanced carbon stocks can increase the value of forest land as ecosystem services gain recognition in economic terms (Andrews-Key & Nelson, 2025).

Among the management practices developed to enhance carbon stocks, several authors have suggested that changing stand-level forest management (sustainable forest management) and forming uneven-aged forests may be a fast and cost-efficient mitigation option in areas with high forest cover (Ameray et al., 2021; Griscom et al., 2017; Metsaranta et al., 2023; Poorter et al., 2015), as is the case with the private forests in the Clearwater Valley surrounded by the forests of Wells Gray Provincial Park. In uneven-aged forestry, the stand is managed by thinning only, and natural regeneration leads to a heterogeneous age and size distribution to reduce competition among trees (Clay et al., 2019). Compared to rotation forestry, management that continuously maintains forest cover is likely to support more ecosystem services and to improve resilience against climate change (Assmuth et al., 2021).

Despite the benefits private landowners can obtain from the rise of carbon stocks in the form of ecosystem services and payment for them, it is crucial to consider several risks to account for in adaptation to carbon enhancement practices. From a natural perspective, catastrophic events such as the Mountain Pine Beetle epidemic in BC and an increase in wildfire threat have contributed to the accelerated implementation of adaptation practices in the province that are designed to protect vegetation (Antwi et al., 2023). Other contributing factors are legal and policy capacity within governments, funding, support from higher levels of government (Rayner et al. 2013; Keenan 2015), risk perception and direct experiences with climate hazards (Christianson et al. 2013; Devisscher et al. 2019).

The importance of the role of private lands in rising carbon stocks and sequestration rates can be overshadowed by an inefficient land planning strategy to integrate these new potential carbon stocks into the pre-existing carbon stocks in legally protected areas. An essential principle to assess and plan functional habitat networks is the better, bigger, more and joined (Lawton et al., 2010). This approach is a key principle for ranking local landscapes concerning where to focus on establishing protected areas or initiating landscape and nature restoration (Bubnicki et al., 2024). It is imperative to identify areas where private landowners' conservation ambitions are higher so that enhancement practices can be prioritized. Also, where ambitions may be lower, there is a need for identification so that the forest can support continued controlled and sustainable stems harvesting, such as wood biomass production, climate-smart forestry approaches, or closer-to-nature management alternatives, depending on the local premises.

The potential expansion of private forests in the Upper Clearwater Valley

The Upper Clearwater Valley has a distinctive natural history and ecological setting that diverges from the rest of the Clearwater District. These features have provoked a deep connection to the land for the valley's residents and visitors, manifested by appreciation of the status of the landscape and a sincere concern about its future. A large number of private landowners in the valley are willing to implement practices that enhance carbon stocks, sequestration and other ecosystem services. To achieve this, a strategic plan must be developed for the areas to intervene to raise carbon stocks that can serve as an example to other landowners or the community to keep expanding the private forest network.

Several factors need to be considered to configure an efficient forest corridor that can successfully increase carbon stock and provide habitat to wildlife. The proximity to road networks and industry, existing land cover, health of vegetation, and forestland ownership status must be considered. This is particularly the case when concerning non-industrial private and private forest company ownership (Bubnicki et al., 2024). Once these factors are assessed, it is possible to prioritize the implementation of appropriate carbon stock enhancement practices (Zonneveld, 1989).

Given the broad spectrum of factors required to determine the land units necessary to expand forests with the capacity to increase carbon in the study area, it is essential to decide which zones could hold the greatest potential to increase carbon stocks based on at least some of the factors mentioned previously. For that purpose, a good starting point is to analyze the current land-cover composition of the Upper Clearwater Valley around the privately protected forest, and then determine how much area could be used for carbon enhancement.

Based on Figure 3.6, the Upper Clearwater Valley is dominated by Tree cover (44.7 million m²), a positive carbon storage starting point. Only 37.22% of this forested area is on private land, meaning the majority is likely under public or other ownership. This highlights the importance of engaging private landowners to connect and expand this forest network. The rangeland can be a prime candidate for afforestation, reforestation, or improved grazing management that increases soil carbon and biomass. Its ecological homogeneity and the fact that it is 90% owned by private landowners make it suitable for implementing carbon-enhancing actions under the lens of other socioeconomic factors. The spatial configuration of rangelands and forested areas is vital for decision-making to determine the optimal size, shape, and topographic direction of the forest subject to management.

To create an efficient forest network that increases carbon stocks, the strategic plan could first engage with the owners of the private parcels with forests that are already connected to Wells Gray Provincial Park and/or this research study area. Since the ecological connectivity of patches and building corridors will allow the vegetation to thrive by facilitating the movement and establishment of various tree species that contribute to overall carbon density. Besides this, any improved forest management practice can be reinforced by natural regeneration from the already well-established protected forest, either from the park or a private protected forest. Most of the rangelands located north of the study area represent an ecological disconnection of the forest in the valley.

The private non-protected forests in the valley that are connected to Wells Gray Provincial Park’s forest could be treated, from the landscape ecology perspective, as a single land unit that represents an opportunity to develop an avoided conversion project nourished by natural forest regrowth to transform early and mid-successional forests into secondary forests. Natural forest regrowth can cost less than intensive tree planting and promote the re-establishment of local biodiversity (Ameray et al., 2021; Lawton et al., 2010; Payne et al., 2019). Cook-Patton et al. (2020) found that naturally regrowing forests can match or exceed actively restored ones, but this may reflect bias toward favourable sites; regrowth is often limited by land degradation and distant seed sources.

Even though natural regrowth is a passive practice, landowners can leverage natural processes to build more diverse and carbon-rich forest ecosystems. Integrating agroforestry systems in private lands can create mixed-use landscapes that enhance carbon stocks while providing economic benefits. Evidence indicates that agroforestry supports diverse plant communities, leading to increased soil carbon storage and improved ecosystem services (Ameray et al., 2021; Lawton et al., 2010; Schuldt et al., 2023). This approach aligns with land-use strategies that maximize carbon sequestration and agricultural productivity.

Rangelands represent the largest, most contiguous, and most readily available opportunity for significant carbon stock enhancement through land cover change, afforestation and improved private property management in the Upper Clearwater Valley. The optimization of grazing practices is crucial to enhance carbon stocks in rangeland ecosystems. Rotational grazing, moderate stocking rates, and grazing optimization strategies can positively impact soil carbon sequestration by preventing overgrazing and allowing vegetation to recover (Conant & Paustian, 2002; Fargione et al., 2018). When degradation is addressed through landscaping techniques and agroforestry, such as restoring native grasses and tree planting, it can increase biodiversity, reduce erosion, and enhance carbon capture (Fargione et al., 2018).

Carbon stocks rising in private forests is critical for meeting local, provincial, and national climate change policy goals. The establishment of robust monitoring systems to quantify carbon stocks accurately is vital for evaluating progress on the increase in carbon stocks or rates and achieving local goals regarding carbon emissions reduction. Clay et al. (2019) discuss the importance of verification systems in tracking changes in carbon stocks and ensuring effective management practices. Indeed, the use of technology such as remote sensing, as used in this research, can enhance the assessment of carbon stocks and inform adaptive management strategies (Coffield et al., 2022).

In the case of the private landowners in the Upper Clearwater Valley, most landowners are aware of the importance of conserving forests, the possible outputs of implementing strategies to manage forests for climate adaptation, and the consequences of not doing so. Despite this, achieving a successful forest expansion requires other landowners to join the project, and it is through education that the awareness of the importance of this ecosystem service can be increased. Workshops and training programs can empower landowners with knowledge about effective practices that support carbon sequestration and sustainable land use, to reinforce the broader goals of conservation and climate change mitigation.

CONCLUSION

The predictive biomass model successfully captured the spatial heterogeneity of the study area due to a shift in the importance of the topographic and forest structure variables for each side of the study area. The western area's biomass was primarily a function of tree size, while the eastern area exhibited a more complex interaction between tree size, canopy structure and topography. Although the model accuracies (49.61% for the west and 57.85% for the east) are within the reported range for Random Forest ecological modelling, they highlight the challenges of predicting the interactions among local variables. This underscores the need for future models that can integrate additional data sources, such as multispectral imagery.

The estimated total carbon density of 165.48 Mg C/ha significantly exceeds values derived from national-scale models. This demonstrates the importance of fine-scale analysis for capturing landscape features. The results suggest that the carbon stock in the privately protected forest of the valley is characterized as a mid-successional, mixed-species forest, regenerating from historical wildfires. Key species like white birch, trembling aspen, and white spruce form a foundation for substantial carbon storage, with the potential for further accumulation as the forest matures. Considering these characteristics and that the valley is part of a crucial ecological reservoir in the high-carbon-density Interior Cedar-Hemlock (ICH) zone, the maintenance and expansion of private protected forests is imperative under projected climate shifts threatening these subalpine ecosystems. Furthermore, the privately protected forest sequesters 0.47 Mt C/yr, a rate that demonstrates a high local capacity for mitigating local greenhouse gas emissions. This sequestration occurs within a forest transitioning from mid-successional to early old-growth stages. This successional stage represents that the forests will enhance their structural complexity, biodiversity, and long-term resilience to climate change effects such as wildfire.

Effective management and expansion of private forests in the Upper Clearwater Valley are essential to enhance carbon stocks, as only 37.22% of the predominant forest cover is on private land, most of which is connected to Wells Gray Provincial Park. Moreover, the valley's almost entirely privately owned rangelands present a substantial opportunity for carbon enhancement outside the already forested areas. A strategic roadmap to increase carbon stocks should engage private forest owners connected to Wells Gray Provincial Park to implement natural regrowth to develop secondary forests with higher carbon density. This effort proves cost-effective and supports local biodiversity by utilizing seed sources from established protected forests. The rangelands in the north of the study area are ideal to implement afforestation, reforestation, and improved grazing management, to form forest corridors that connect existing private forest patches. Ultimately, this can boost landscape-scale carbon stocks.

The successful implementation of this strategy requires addressing social factors. First, valley residents' deep connection to the land is a major asset since any plan must integrally include residents' perceptions of land management to identify and prioritize areas where carbon stock enhancement practices could be successful according to the community's expectations. Second, only the example of a well-established project, such as the aggregated parcels of this research study area, can demonstrate to neighbouring landowners the feasibility of having portions of forest protected in their properties. It is crucial to know landowners' perspectives on conservation purposes versus forest harvesting. The engagement of landowners with carbon benefits and the facilitation of their access to carbon credit markets can provide the financial motivation for widespread adoption of enhancement practices. Third, economic incentives are crucial to keep working on the current conservation of the forest in the forests studied and for expanding the forest to neighbouring properties to connect the valley to the protected area.

The Upper Clearwater Valley has exceptional ecological value, possesses significant and growing carbon stocks and a carbon sequestration rate promising to offset greenhouse gas emissions locally. This research provides the scientific foundation and a strategic plan to leverage this potential. The valley can serve as a model for climate mitigation through the prioritization of ecological connectivity along forest patches, the pursue of develop the high-potential of private rangelands, and the implementation of a mix of conservation, natural regrowth, and active management. The protection and landscape management of this area is not merely a local conservation effort but a vital investment in a resilient ecological reservoir that will safeguard biodiversity and regulate the climate for future generations.

REFERENCES

Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., & Cavard, X. (2021). Forest Carbon Management: A Review of Silvicultural Practices and Management Strategies Across Boreal, Temperate and Tropical Forests. *Current Forestry Reports*, *7*(4), 245–266. https://doi.org/10.1007/s40725-021-00151-w

Andrews-Key, S. A., & Nelson, H. (2025). Using climate vulnerability assessments to implement and mainstream adaptation by the forest industry into forest management in Canada. *Frontiers in Forests and Global Change*, *8*, 1434585. https://doi.org/10.3389/ffgc.2025.1434585

Antwi, E. K., Burkhardt, H., Boakye-Danquah, J., Doucet, T., & Abolina, E. (2023). Review of climate change adaptation and mitigation implementation in Canada’s forest ecosystems part I: Reporting, science, and institutional/governance supporting practices in Canada. *Environmental Reviews*, er-2022-0130. https://doi.org/10.1139/er-2022-0130

Assmuth, A., Rämö, J., & Tahvonen, O. (2021). Optimal Carbon Storage in Mixed-Species Size-Structured Forests. *Environmental and Resource Economics*, *79*(2), 249–275. https://doi.org/10.1007/s10640-021-00559-9

Bechtold, W. A., & Patterson, P. L. (2015). *The Enhanced Forest Inventory and Analysis Program � National Sampling Design and Estimation Procedures* (No. SRS-GTR-80; p. SRS-GTR-80). U.S. Department of Agriculture, Forest Service, Southern Research Station. https://doi.org/10.2737/SRS-GTR-80

Boudewyn, P., Song, X., Magnussen, S., & Gillis, M. D. (2007). *Model-based, volume to biomass conversion for forested and vegetated land in Canada* (Information Report No. BC-X-411; Canadian Forest Service). Natural Resources Canada. https://ostr-backend-prod.azure.cloud.nrcan-rncan.gc.ca/server/api/core/bitstreams/8b8f0000-278b-4ba0-baa7-9c1cf333d8ae/content

Bubnicki, J. W., Angelstam, P., Mikusiński, G., Svensson, J., & Jonsson, B. G. (2024). The conservation value of forests can be predicted at the scale of 1 hectare. *Communications Earth & Environment*, *5*(1), 196. https://doi.org/10.1038/s43247-024-01325-7

Canadian Council of Forest Ministers. (2022). The Canadian Council of Forest Ministers’ framework of Criteria and Indicators of Sustainable Forest Management in Canada—Canadian Council of Forest Ministers (CCFM). Canadian Council of Forest Ministers (CCFM). https://www.ccfm.org/releases/framework-of-criteria-and-indicators-of-sustainable-forest-management-in-canada/

Chen, L., Ren, C., Zhang, B., Wang, Z., & Xi, Y. (2018). Estimation of Forest Above-Ground Biomass by Geographically Weighted Regression and Machine Learning with Sentinel Imagery. *Forests*, *9*(10), 582. https://doi.org/10.3390/f9100582

Chen, X., Reich, P. B., Taylor, A. R., An, Z., & Chang, S. X. (2024). Resource availability enhances positive tree functional diversity effects on carbon and nitrogen accrual in natural forests. *Nature Communications*, *15*(1), 8615. https://doi.org/10.1038/s41467-024-53004-y

Cheung, N. (2024). *Exploring Tools and Methods for Assessing Carbon Sequestration in Parkland*. The City of Surrey. https://sustain.ubc.ca/sites/default/files/2024-

064_Methods_for_Assessing_Carbon_in_Parkland_Cheung_0.pdf#:~:text=To%20better%20manage%20natural%20ecosystems%20and%20achieve,dioxide)%20from%20both%20natural%20and%20anthropogenic%20sources.

Clay, L., Motallebi, M., & Song, B. (2019). An Analysis of Common Forest Management Practices for Carbon Sequestration in South Carolina. *Forests*, *10*(11), 949. https://doi.org/10.3390/f10110949

Coffield, S. R., Vo, C. D., Wang, J. A., Badgley, G., Goulden, M. L., Cullenward, D., Anderegg, W. R. L., & Randerson, J. T. (2022). Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. *Global Change Biology*, *28*(22), 6789–6806. https://doi.org/10.1111/gcb.16380

Conant, R. T., & Paustian, K. (2002). Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochemical Cycles*, *16*(4). https://doi.org/10.1029/2001GB001661

Cook-Patton, S. C., Leavitt, S. M., Gibbs, D., Harris, N. L., Lister, K., Anderson-Teixeira, K. J., Briggs, R. D., Chazdon, R. L., Crowther, T. W., Ellis, P. W., Griscom, H. P., Herrmann, V., Holl, K. D., Houghton, R. A., Larrosa, C., Lomax, G., Lucas, R., Madsen, P., Malhi, Y., … Griscom, B. W. (2020). Mapping carbon accumulation potential from global natural forest regrowth. *Nature*, *585*(7826), 545–550. https://doi.org/10.1038/s41586-020-2686-x

Cutler, D. R., Edwards, T. C., Beard, K. H., Cutler, A., Hess, K. T., Gibson, J., & Lawler, J. J. (2007). RANDOM FORESTS FOR CLASSIFICATION IN ECOLOGY. *Ecology*, *88*(11), 2783–2792. https://doi.org/10.1890/07-0539.1

Davies, A. B., & Asner, G. P. (2014). Advances in animal ecology from 3D-LiDAR ecosystem mapping. *Trends in Ecology & Evolution*, *29*(12), 681–691. https://doi.org/10.1016/j.tree.2014.10.005

Demarchi, D. (2011). *An Introduction to the Ecoregions of British Columbia* (Ecosystem Information Section). Ministry of Environment of British Columbia. https://www2.gov.bc.ca/assets/gov/environment/plants-animals-and-ecosystems/ecosystems/broad-ecosystem/an_introduction_to_the_ecoregions_of_british_columbia.pdf

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., Falcucci, A., Fourqurean, J. W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M. D., Kroeger, K. D., Kroeger, T., Lark, T. J., Leavitt, S. M., Lomax, G., McDonald, R. I., … Griscom, B. W. (2018). Natural climate solutions for the United States. *Science Advances*, *4*(11), eaat1869. https://doi.org/10.1126/sciadv.aat1869

Freund, J. A., Franklin, J. F., & Lutz, J. A. (2015). Structure of early old-growth Douglas-fir forests in the Pacific Northwest. *Forest Ecology and Management*, *335*, 11–25. https://doi.org/10.1016/j.foreco.2014.08.023

Gifford, R., Brown, C., Baron, C., Clement, D., Melnychuk, N., Nelson, H., Sales, L., & Spittlehouse, D. (2022). *British Columbia Chapter in Canada in a Changing Climate* (Regional Perspectives Report, p. 76). Government of Canada. https://publications.gc.ca/collections/collection_2023/rncan-nrcan/M174-25-2021-5-eng.pdf

Goward, T. (2024). *Edgewood Blue*. Edgewood Wild. https://edgewoodwild.org/edgewood-home/edgewood-blue/

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Hanes, C. C., Wang, X., Jain, P., Parisien, M.-A., Little, J. M., & Flannigan, M. D. (2019). Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, *49*(3), 256–269. https://doi.org/10.1139/cjfr-2018-0293

Hood, W. G., & Naiman, R. J. (2000). Vulnerability of riparian zones to invasion by exotic vascular plants. *Plant Ecology*, *148*(1), 105–114. https://doi.org/10.1023/A:1009800327334

Hoover, C. M., & Smith, J. E. (2023). Aboveground live tree carbon stock and change in forests of conterminous United States: Influence of stand age. *Carbon Balance and Management*, *18*(1), 7. https://doi.org/10.1186/s13021-023-00227-z

Hu, Y., Xu, X., Wu, F., Sun, Z., Xia, H., Meng, Q., Huang, W., Zhou, H., Gao, J., Li, W., Peng, D., & Xiao, X. (2020). Estimating Forest Stock Volume in Hunan Province, China, by Integrating In Situ Plot Data, Sentinel-2 Images, and Linear and Machine Learning Regression Models. *Remote Sensing*, *12*(1), 186. https://doi.org/10.3390/rs12010186

Iversen, S., Holt, C., Van Der Velden, N., Mansfield, L., Convery, I., Kjeldsen, C., & Thorsøe, M. (2021). *Impacts of woodland planting on nature-based recreational tourism in upland England – a case study*. Social and Behavioral Sciences. https://doi.org/10.32942/OSF.IO/UR6QZ

Jia, N., & He, Z. (2023). Assessment of the Potential Capacity of Carbon Sequestration of forest. *Highlights in Science, Engineering and Technology*, *48*, 112–118. https://doi.org/10.54097/hset.v48i.8283

Klinkenberg, B. (2023). *E-Flora BC: Electronic Atlas of the Flora of British Columbia*. Lab for Advanced Spatial Analysis, Department of Geography, University of British Columbia, Vancouver. https://linnet.geog.ubc.ca/biodiversity/eflora/TerrestrialVegetation.html

Krenke, A. N., Ptichnikov, A. V., Shvarts, E. A., & Petrov, I. K. (2021). Assessments of the Forest Carbon Balance in the National Climate Policies of Russia and Canada. *Doklady Earth Sciences*, *501*(2), 1091–1095. https://doi.org/10.1134/S1028334X21120060

Kurz, W. A., Shaw, C. H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., Dyk, A., Smyth, C., & Neilson, E. T. (2013). Carbon in Canada's boreal forest—A synthesis. *Environmental Reviews*, *21*(4), 260–292. https://doi.org/10.1139/er-2013-0041

Lang, M., Binder, M., Richter, J., Schratz, P., Pfisterer, F., Coors, S., Au, Q., Casalicchio, G., Kotthoff, L., & Bischl, B. (2019). mlr3: A modern object-oriented machine learning framework in R. *Journal of Open Source Software*, *4*(44), 1903. https://doi.org/10.21105/joss.01903

Lawton, J., Valerie Brown, Elphick, C., Fitter, A., Forshaw, J., Haddow, R., Hilborne, S., Leafe, R., Mace, G., Southgate, M., Sutherland, W., Tew, T., Varley, J., & Wynne, G. (2010). *Making Space for Nature: A review of England's wildlife sites and ecological network*. Defra.

Li, X., Ciais, P., Fensholt, R., Chave, J., Sitch, S., Canadell, J. G., Brandt, M., Fan, L., Xiao, X., Tao, S., Wang, H., Albergel, C., Yang, H., Frappart, F., Wang, M., Bastos, A., Maisongrande, P., Qin, Y., Xing, Z., … Wigneron, J.-P. (2025). Large live biomass carbon losses from droughts in the northern temperate ecosystems during 2016-2022. *Nature Communications*, *16*(1), 4980. https://doi.org/10.1038/s41467-025-59999-2

Liang, S., Hurteau, M. D., & Westerling, A. L. (2017). Potential decline in carbon carrying capacity under projected climate-wildfire interactions in the Sierra Nevada. *Scientific Reports*, *7*(1), 2420. https://doi.org/10.1038/s41598-017-02686-0

Liu, C., Chen, D., Zou, C., Liu, S., Li, H., Liu, Z., Feng, W., Zhang, N., & Ye, L. (2022). Modeling Biomass for Natural Subtropical Secondary Forest Using Multi-Source Data and Different Regression Models in Huangfu Mountain, China. *Sustainability*, *14*(20), 13006. https://doi.org/10.3390/su142013006

Maesano, M., Santopuoli, G., Moresi, F., Matteucci, G., Lasserre, B., & Scarascia Mugnozza, G. (2022). Above ground biomass estimation from UAV high resolution RGB images and LiDAR data in a pine forest in Southern Italy. *iForest - Biogeosciences and Forestry*, *15*(6), 451–457. https://doi.org/10.3832/ifor3781-015

Metsaranta, J. M., Hudson, B., Smyth, C., Fellows, M., & Kurz, W. A. (2023). Future fire risk and the greenhouse gas mitigation potential of forest rehabilitation in British Columbia, Canada. *Forest Ecology and Management*, *529*, 120729. https://doi.org/10.1016/j.foreco.2022.120729

Meyer, H., Reudenbach, C., Wöllauer, S., & Nauss, T. (2019). Importance of spatial predictor variable selection in machine learning applications – Moving from data reproduction to spatial prediction. *Ecological Modelling*, *411*, 108815. https://doi.org/10.1016/j.ecolmodel.2019.108815

Mina, M., Messier, C., Duveneck, M. J., Fortin, M., & Aquilué, N. (2022). Managing for the unexpected: Building resilient forest landscapes to cope with global change. *Global Change Biology*, *28*(14), 4323–4341. https://doi.org/10.1111/gcb.16197

Ministry of Forests, Lands and Natural Resource Operations. (2011). *CROWN LAND: Indicators & Statistics Report* (No. 2010). Province of British Columbia. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/natural-resource-use/land-water-use/crown-land/crown_land_indicators__statistics_report.pdf

Mitchell, M., & Bullen, C. (2020, October). Ecosystem Services Assessment for British Columbia's Interior Temperate Rainforest, Upper Columbia Region, and Southern Mountain Caribou Populations. Yellowstone Conservation Initiative. https://y2y.net/wp-content/uploads/2021/03/10.2020-ecosystem-services.pdf

Munteanu, C., Senf, C., Nita, M. D., Sabatini, F. M., Oeser, J., Seidl, R., & Kuemmerle, T. (2022). Using historical spy satellite photographs and recent remote sensing data to identify high-conservation-value forests. *Conservation Biology*, *36*(2), e13820. https://doi.org/10.1111/cobi.13820

Nowak, D. & USDA Forest Service's Northern Research Station. (2021). *Understanding i-Tree: 2021 Summary of Programs and Methods*. https://www.itreetools.org/documents/650/i-Tree_Methods_gtr_nrs200-2021.pdf

Payne, N. J., Allan Cameron, D., Leblanc, J.-D., & Morrison, I. K. (2019). Carbon storage and net primary productivity in Canadian boreal mixedwood stands. *Journal of Forestry Research*, *30*(5), 1667–1678. https://doi.org/10.1007/s11676-019-00886-0

Ploton, P., Mortier, F., Réjou-Méchain, M., Barbier, N., Picard, N., Rossi, V., Dormann, C., Cornu, G., Viennois, G., Bayol, N., Lyapustin, A., Gourlet-Fleury, S., & Pélissier, R. (2020). Spatial validation reveals poor predictive performance of large-scale ecological mapping models. *Nature Communications*, *11*(1), 4540. https://doi.org/10.1038/s41467-020-18321-y

Poorter, L., Van Der Sande, M. T., Thompson, J., Arets, E. J. M. M., Alarcón, A., Álvarez-Sánchez, J., Ascarrunz, N., Balvanera, P., Barajas-Guzmán, G., Boit, A., Bongers, F., Carvalho, F. A., Casanoves, F., Cornejo-Tenorio, G., Costa, F. R. C., De Castilho, C. V., Duivenvoorden, J. F., Dutrieux, L. P., Enquist, B. J., … Peña-Claros, M. (2015). Diversity enhances carbon storage in tropical forests. *Global Ecology and Biogeography*, *24*(11), 1314–1328. https://doi.org/10.1111/geb.12364

Randazzo, N. A., Gordon, D. R., & Hamburg, S. P. (2023). Improved assessment of baseline and additionality for forest carbon crediting. *Ecological Applications*, *33*(3), e2817. https://doi.org/10.1002/eap.2817

Roussel, J.-R., Auty, D., Coops, N. C., Tompalski, P., Goodbody, T. R. H., Meador, A. S., Bourdon, J.-F., De Boissieu, F., & Achim, A. (2020). lidR: An R package for analysis of Airborne Laser Scanning (ALS) data. *Remote Sensing of Environment*, *251*, 112061. https://doi.org/10.1016/j.rse.2020.112061

Schirpke, U., Kohler, M., Leitinger, G., Fontana, V., Tasser, E., & Tappeiner, U. (2017). Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. *Ecosystem Services*, *26*, 79–94. https://doi.org/10.1016/j.ecoser.2017.06.008

Schuldt, A., Liu, X., Buscot, F., Bruelheide, H., Erfmeier, A., He, J., Klein, A., Ma, K., Scherer-Lorenzen, M., Schmid, B., Scholten, T., Tang, Z., Trogisch, S., Wirth, C., Wubet, T., & Staab, M. (2023). Carbon–biodiversity relationships in a highly diverse subtropical forest. *Global Change Biology*, *29*(18), 5321–5333. https://doi.org/10.1111/gcb.16697

Sharma, T., Kurz, W. A., Fellows, M., MacDonald, A. L., Richards, J., Chirsholm, C., Seutin, G., Richardson, K., & Keenleyside, K. (2023). *Parks Canada Carbon Atlas Series: Carbon Dynamics in the Forests of National Parks in Canada* [Scientific Report]. Parks Canada Agency. https://publications.gc.ca/collections/collection_2024/pc/R62-581-2023-eng.pdf

Springer, K., Manning, P., Boesing, A. L., Ammer, C., Fiore-Donno, A. M., Fischer, M., Goldmann, K., Le Provost, G., Overmann, J., Ruess, L., Schöning, I., Seibold, S., Sikorski, J., & Neyret, M. (2024). *Old, broad-leaved stands support both high biodiversity and carbon storage in German forests*. Ecology. https://doi.org/10.1101/2024.02.06.578731

Ter-Mikaelian, M. T., Colombo, S. J., & Chen, J. (2021). Harvest volumes and carbon stocks in boreal forests of Ontario, Canada. *The Forestry Chronicle*, *97*(02), 168–178. https://doi.org/10.5558/tfc2021-018

Triviño, M., Juutinen, A., Mazziotta, A., Miettinen, K., Podkopaev, D., Reunanen, P., & Mönkkönen, M. (2015). Managing a boreal forest landscape for providing timber, storing and sequestering carbon. *Ecosystem Services*, *14*, 179–189. https://doi.org/10.1016/j.ecoser.2015.02.003

WWF Canada. (2024). *Measuring carbon in trees: A supplemental guide* [Supplemental Guide]. World Wildlife Fund Canada. https://wwf.ca/wp-content/uploads/2024/07/Trees-FINAL.pdf

Yang, H., Ciais, P., Frappart, F., Li, X., Brandt, M., Fensholt, R., Fan, L., Saatchi, S., Besnard, S., Deng, Z., Bowring, S., & Wigneron, J.-P. (2023). Global increase in biomass carbon stock dominated by growth of northern young forests over past decade. *Nature Geoscience*, *16*(10), 886–892. https://doi.org/10.1038/s41561-023-01274-4

Zonneveld, I. S. (1989). The land unit ? A fundamental concept in landscape ecology, and its applications. *Landscape Ecology*, *3*(2), 67–86. https://doi.org/10.1007/BF00131171

Chapter 4. The Economics of Forest Carbon Sequestration Enhancement in the Upper Clearwater Valley

INTRODUCTION

The commodification of carbon has emerged as a central pillar in contemporary climate policy and environmental economics, both globally and within Canada. As governments and industries seek to decarbonize their operations in response to national commitments under the Paris Agreement and evolving public expectations, carbon offset markets have become an increasingly important mechanism to reduce net emissions (Government of Canada, 2017). Thus, when carbon has a measurable, tradable value, sustainable practices become more economically viable, especially in areas that face pressure from forestry or development (Riany et al., 2024).

With carbon as a commodity, climate change fight goals can be achieved through innovation in land-use planning and sustainable agricultural and forestry practices by provincial and federal governments. The Government of Canada has initiated large-scale afforestation projects aimed at promoting carbon sequestration, thus reinforcing the role of carbon management in fostering innovative agroforestry practices (Government of British Columbia, 2025e). Furthermore, the increase in carbon storage through carbon markets has been demonstrated to be cost-effective and scalable compared to technological alternatives (Government of Canada, 2025b).

In BC, where vast forested landscapes act as powerful carbon sinks, carbon offset projects, particularly those based on forest conservation and restoration, have gained attention for their environmental benefits and economic potential. The provincial carbon market, operating under BC’s Greenhouse Gas Industrial Reporting and Control Act and the voluntary carbon market, has created opportunities for landowners and Indigenous communities to generate revenue through carbon credit sales (BC Ministry of Environment and Climate Change Strategy, 2022). This new economic activity represents financial incentives for landowners, Indigenous communities, and forest managers to adopt land-use practices that promote the improvement of ecosystem services and create economic sustainability for local communities (Council of Canadian Academies, 2022b).

Given the growing economic significance of carbon markets in Canada as a tool for climate change mitigation and forest conservation, the Upper Clearwater Valley community has demonstrated advocacy for forest protection and the maintenance of ecosystem services. The valley's forests are highly valued, supporting economic activities as tourism and forestry. Crucially, their carbon storage and sequestration capacity have been demonstrated to be comparable to that of mid-successional forests in the nearby Wells Gray Provincial Park. I argue that carbon offset initiatives can provide a viable alternative source of income for the rural community of Clearwater. Therefore, this research posits that a monetary valuation of this existing carbon sequestration service is a critical first step in understanding its role in the local economy and the viability of a carbon offset project.

This chapter conducts a non-market valuation of the carbon sequestration service provided by the valley's forests. This is examined by estimating the economic value of the valley's carbon sequestration capacity using data from Chapter 3 and applying three different shadow prices: values from both the BC compliance and voluntary carbon markets, as well as the global Social Cost of Carbon. This exercise does not estimate potential revenue from a future carbon credit project but rather quantifies the existing natural capital asset to inform discussions on socioeconomic diversification and the full cost-benefit analysis of conservation for the Upper Clearwater Valley.

SOCIOECONOMIC DIVERSIFICATION IN THE VALLEY

Clearwater has historically been a forest-dependent town. Nevertheless, the forest industry has recently lost its local wood processing capacity. According to the District of Clearwater (2022), forestry remains the town's most dominant industry, while tourism is the most rapidly expanding sector. Climate change and the increasing wildfire frequency and severity threaten the economic activities supported by natural resources. Relying on a single industrial sector exposes rural towns to substantial challenges and risks. Researchers suggest that ecotourism could diversify local economies, but this shift may face resistance from various stakeholders, leading to development tensions (Connell et al., 2017). As climate change exacerbates these issues, effective land use planning becomes essential to address conflicts among governments, resource industries, and tourism operators (Mason and Neumann, 2024).

As society is consuming natural capital at an alarmingly high rate, it is critical to shift our relationship with the natural world to one that acknowledges the economy's dependence on natural capital and accepts the bounds that nature places on economic sustainability (Simpson et al., 2021). Commodifying well-managed ecosystem services under a long-term maintenance approach can serve several purposes where climate policy, forest resources, and economic interests intersect (Antwi et al., 2023). Nature-based economies represent an alternative opportunity to address economic diversification and environmental crisis in areas experiencing a decline in economic activity in traditional natural resource sectors (Council of Canadian Academies, 2022b).

Clearwater's core strengths are its natural environment, location, affordability, and amenities, which are considered above average for a community of its size (District of Clearwater, 2021). Tourism is often highlighted as a way to diversify the local economy (Connell et al., 2017). Although small in scale, agriculture still represents substantial importance to the local economy (District of Clearwater, 2021). While the forestry industries remain important, their footprint in rural communities has been declining since the 1980s (District of Clearwater, 2021). The Clearwater District economic development plan highlights tourism as a significant driver of economic diversification. However, it fails to acknowledge the natural capital essential for the success of the tourism industry. The only reference to forest valuation within the plan pertains to Wells Gray Provincial Park, which is positioned as a strategic asset for the local tourism sector (District of Clearwater, 2021).

Nature-based solutions that involve forest conservation and management are not yet part of the district planning or local stakeholders' development projections. Interestingly, most stakeholders interviewed did not view the vegetation of the valley forest as economically valuable beyond timber extraction. While ecotourism is well established and benefits from forested landscapes, it focuses on visitor services rather than resource use. Government-led forest carbon initiatives, such as BC’s Forest Carbon Initiative, offer effective examples of nature-based solutions. When properly designed, forest ecosystems can be managed to deliver measurable atmospheric benefits. The initiative seeks to reduce emissions and enhance carbon sequestration through improved forest practices, land-based investments, and outreach programs, aligning with provincial and federal climate goals (Government of British Columbia, 2024b). However, public uptake remains limited, largely due to perceptions that such programs require significant resources, often beyond the reach of potential applicants.

Most forest carbon projects are designed and implemented by non-profit organizations, private companies, or groups of landowners (aggregated projects) that aim to maximize forest benefits while protecting its natural characteristics. Forest-based carbon projects offer a unique opportunity to align economic development with ecological preservation and support livelihoods. The success of this type of project largely depends on establishing a realistic and credible baseline scenario for emissions and implementing practical forest management activities. The project’s activities must lead to modifications in the conditions outlined in the baseline scenario that result in actual reductions in emissions (ClimeCo, 2024).

FOREST CARBON OFFSET PROJECTS (FCOP)

Driven by environmental targets and political developments, Canada’s carbon pricing policy regime continues to evolve. As a result, ongoing shifts create challenges and opportunities for businesses, since balancing carbon costs with competitiveness, innovation, and sustainability is now a core business concern (Dunkelman, 2025). The policy-making and regulation surrounding national carbon markets and carbon offset projects enable Canada to participate in global voluntary markets, thereby increasing international collaboration and funding for Canadian projects that meet recognized standards (BC Ministry of Environment and Climate Change Strategy, 2022), which boosts credibility and transparency.

In this context, BC offers a telling example: absolute emissions have dropped by 5% compared to the pre-carbon tax period, and sales of fossil fuel products declined by 17% (Citizens Climate Lobby, 2023). Economists estimate that carbon pricing in BC has resulted in a 5% to 15% cut in emissions compared to a scenario without carbon pricing (Citizens Climate Lobby, 2023). That is why many businesses have pursued emissions reductions through forest carbon offset projects as an alternative means for earning certified emission reduction credits, particularly under the rubric of reducing emissions from deforestation and forest degradation (Van Kooten et al., 2015).

Yet, forest carbon offsetting projects can face high initial costs, complex verification standards, and uncertainties around long-term carbon permanence. Critics also argue that carbon markets can enable large polluters to delay real emissions reductions, raising questions of environmental justice and market integrity (ClimeCo, 2024). For rural communities, navigating carbon projects' technical, regulatory, social and financial aspects requires capacity-building and support (Council of Canadian Academies, 2022b). Unless climate change risk factors are fully considered when assessing the long-term consequences of different GHG emissions reduction strategies, there is potential for proposed solutions to result in increased costs over time (Gifford et al., 2022).

Forest Carbon Offset Project Implementation

To implement a forest carbon offset project in BC, it is crucial to assess its viability based on preliminary research into the ecological and socioeconomic dimensions. The first step is clearly defining the project type. Each type of project has different eligibility criteria and monitoring requirements based on the area's extension availability, the carbon sequestration capacity, and the health of pre-existing vegetation and soil (Citizens Climate Lobby, 2023). This ecological aspect was previously discussed in Chapter 3 of this thesis, where the study area's carbon sequestration capacity was modelled, and the potential geographical implications of their expansion were discussed.

To effectively address the project's social implications at all levels of society, it is essential to build on foundational scientific research. The project must be assessed for compliance with recognized federal or provincial protocols or voluntary market standards (Ministry of Environment and Climate Change Strategy, 2024). It is essential to verify legal land ownership and management rights (Clean BC, 2025; Cline, 2024; Haley & Nelson, 2007). Early stakeholder engagement is critical to identifying potential co-benefits or barriers. As outlined in Chapter 2 of this thesis, social aspects, including the current provincial regulations for the study area, were discussed from the interviewees' perspectives.

The economic projection is the third component of the forest carbon offset project feasibility assessment. As outlined in the BC 2025 Offset Protocol, it is necessary to estimate the implementation costs versus potential returns based on potential carbon credit sales and other revenue streams (Ministry of Environment and Climate Change Strategy, 2024). That includes all potential costs associated with project implementation, including registration fees, field studies, and land management expenses under different scenarios (Citizens Climate Lobby, 2023).

Local Stakeholders' Perceptions of FCOP in British Columbia

As of the latest 2024 BC Carbon Registry portfolio, BC publicly lists 13 offset projects overseen under the Carbon Neutral Government program. These projects span forestry, agriculture, oil & gas, transportation, clean tech, and waste management sectors (Government of British Columbia, 2025e). However, there is an undisclosed number of private-sector or voluntary-registered BC projects. Three different projects were presented to the interviewees to demonstrate successful projects and obtain their insights about their willingness to participate in a feasibility study for implementing a forest carbon offset project in the valley. From an operational perspective, the diversity of project management reveals significant opportunities to enhance carbon sequestration at various spatial scales and engage diverse stakeholders in the projects.

The Great Bear Rainforest was Canada's first carbon offset program and the largest forest carbon project globally. The project encompasses over 780,000 hectares of productive forest land, focusing on improved forest management by protecting areas previously designated for commercial logging. The project is estimated to reduce emissions by 465,841 tonnes of CO_2 (Great Bear Carbon, 2025). Similarly, the Cheakamus Community Forest Carbon Project, encompasses 33,000 hectares near Whistler, implements improved forest management practices to generate carbon offsets from forestry operations, with emphasis on ecosystem-based management (Ecotrust, 2015).

The Darkwoods Forest Carbon Project covers a vast 103,000 hectares in southeastern BC. It connects existing parks and wildlife management areas, forming a contiguous wilderness area of 255,000 acres. This landscape-scale conservation effort is crucial for large species such as grizzly bears and mountain caribou. The Darkwoods Project involves the private acquisition of a fee-simple property with no people living on or relying on the project area for their livelihood. Hence, no direct consultation process was necessary; however, the Nature Conservancy Canada undertook an extensive outreach and public stakeholder communication process in the local communities (Wilson, 2019).

Despite showing the success of those projects, and particularly the last one, which has pre-existing conditions relatable to the Upper Clearwater Valley, most of the interviewees perceived the carbon offset project design and registration as a complex and long-term process. As Dickinson (2025) exposed:

> *There are provincial initiatives, but you have to submit a lot of documentation to get these incentives. And that's a lot of work for an old landowner. And most people don't have the skills or capacity to do that.*

Dickinson's reflections focused on the challenges faced by a single landowner in managing planting and other restoration practices across a vast area, even without a forest project.

Any economic activity can quickly become an overwhelming task for one project proponent. Securing the resources necessary to begin even the feasibility stage can take several months, influenced by the social conditions of the area. From this perspective, the projects previously mentioned were developed on properties owned by a forestry company, which typically manages larger areas and possesses the financial capacity to implement projects and sustain practices until they become profitable.

Another stream could potentially be suitable for the Upper Clearwater Valley, given the diversity of land uses in the area and the presence of The Land Conservancy, which has land conservation agreements. In the local context, it is essential to note that The Land Conservancy's current mission is solely focused on conservation (Personal communication with Catherine Armstrong, 2025). To implement a project like the one proposed by Sunderman would first require The Land Conservancy to consider a mixed-purpose approach. Thus, it would be necessary to identify private lands currently used for agriculture, forestry, or residential purposes that would be appropriate for such a project. This would consider land ownership, usage, and forest connectivity. Finally, landowners and managers must be informed of the project's implications and be willing to agree to The Land Conservancy's terms.

From a distinct stakeholder perspective, the Wells Gray Community Forest Corporation highlighted that the Cheakamus Community Forest is the sole community forest organization in BC that has completed this project. This achievement can be attributed mainly to the residents' strong commitment to environmental sustainability and preservation values that initially supported the project (Personal communication with George Brcko, 2025). Nevertheless, Cheakamus's guidelines for the project registration are no longer recognized by the provincial authorities unless a partnership with local First Nations has been established to develop activities outlined in their atmospheric benefit agreement (Ministry of Environment and Climate Change Strategy, 2024). While community forest corporations are now restricted from independently implementing forest carbon offset projects, the government’s guidelines promote genuine partnerships with Indigenous communities to enhance environmental stewardship and incorporate traditional ecological knowledge.

Carbon Project Opportunity Evaluation

Project Type Selection

The assessment of the opportunity of the forest carbon project in the study area's feasibility must start with the identification of the most favourable type of project to the characteristics of the current and past land use, vegetation management practices to implement, collective objectives towards conservation and compatibility with other local initiatives. As outlined in the British Columbia Greenhouse Gas Offset Protocol: Forest Carbon (2024), three different project types are eligible to produce forest carbon credits in the compliance and voluntary market.

Afforestation, Reforestation, and Revegetation (ARR) projects require converting non-forested land to forested cover. Still, they are unsuitable for areas under community forest licenses or natural regeneration zones, making them more relevant to agricultural or degraded lands. Avoided Conversion (REDD+) projects aim to prevent deforestation. This type of project is only viable if the land has been classified as forest for the past 20 years and faces credible threats of conversion, such as development or agriculture, requiring landowners to demonstrate financial incentives for such changes. Improved Forest Management (IFM) focuses on enhancing existing forest stewardship beyond regulatory norms and is applicable to lands already defined as forest, including old-growth and privately conserved areas, offering broader inclusion of forest fragments across the valley (Ministry of Forests, 2024).

Considering past and current forest management practices, the impacts of climate change on forest cover, and landowners' willingness in the Upper Clearwater Valley to adopt fire-smart strategies for managing forested areas, it is likely that landowners would prefer an IFM carbon project to avoided deforestation. This preference arises from the understanding that land management activities could be subject to more restrictions while aligning with established conservation objectives. The inclusion of local community forest-licensed lands, coupled with a substantial reduction in harvesting, may be more attractive to external landowners seeking to expand the project area.

The protocols for IFM enable working forests to transition to sustainable forests that are more resilient to climate change through maintaining old stands with high carbon storage capacity, but also high growth rates with moderate turnover (ClimeCo, 2024). Forest management practices could include: enrichment planting, enhancing natural regeneration by the management of competing vegetation, stand irrigation and/or fertilization, reducing timber harvest levels, deferring harvest by extending rotations, and altering fire severity by fuel load treatments (Ministry of Environment and Climate Change Strategy, 2024). Verra Verified Carbon Standards, the world's most widely used greenhouse gas crediting program, suggests that projects that are pursuing an Improved Forest Management Carbon Project assume that 25% of the forest will be cleared.

Carbon Storage Projection

The carbon scenario projection involves the construction of two scenarios: the baseline and project scenarios. The baseline scenario establishes the reference conditions for carbon storage projections by identifying land use actors, deforestation drivers, and historical degradation trends, supported by objective data comparisons (ClimeCo, 2024). It is necessary to demonstrate that the project area is under deforestation pressure or has been degraded historically (Ministry of Environment and Climate Change Strategy, 2024). In the Upper Clearwater Valley, the mid-successional forest that regenerated after wildfire demonstrates the vegetation's capacity to recover from natural disturbances despite the current wildfire threats. The valley’s residents engage in various land-based economic activities, including cattle ranching, forestry, and tourism. These practices involve timber harvesting, pasture clearing, and wood production, making timber extraction and livestock use the most plausible baseline scenario.

The project scenario involves interventions to prevent emissions, primarily through avoiding forest clearing and harvesting. Following the BC Forest Carbon Offset Protocol (2024), carbon modelling integrates species-specific carbon dynamics and landscape models that aggregate carbon storage across the area. Carbon credits are calculated by comparing emissions avoided under this scenario to those projected in the baseline (Ministry of Environment and Climate Change Strategy, 2024). The approach emphasizes conserving forests near rural developments and managing them to support biodiversity and habitat restoration. Landowners must commit to protecting forested areas for at least 20 years, ideally up to 50, allowing continued carbon sequestration in biomass and debris. Permitted activities include trail development and wildfire management, provided they do not significantly alter forest carbon stocks (Ministry of Environment and Climate Change Strategy, 2024).

While the protocol establishes a framework for quantifying and crediting forest carbon, its environmental integrity depends on rigorously addressing three foundational issues: additionality, leakage, and permanence (Ministry of Environment and Climate Change Strategy, 2024). Additionally, questions whether the credited carbon sequestration would have occurred without the incentive of the offset program. Leakage examines the risk that reducing emissions or conserving forest in one area may inadvertently shift deforestation or degradation activities to another, uncredited location. Finally, permanence addresses the challenge of ensuring that stored carbon remains sequestered over the long term, particularly given the risks of wildfires, pests, and future land-use changes, which is especially relevant for the program’s 20- to 50-year commitment periods (Ministry of Environment and Climate Change Strategy, 2024).

Costs and Revenue Implications

Assessing the feasibility and long-term sustainability of forest carbon projects is crucial to understanding their financial implications. In 2024, ClimeCo conducted a feasibility report for a carbon offset project with the Coastal Douglas-fir Conservation

Partnership, covering 152 Ha in Metchosin and the Sunshine Coast Regional District. The project features a diverse secondary-growth forest similar to that of the Upper Clearwater Valley, including white spruce and western redcedar. ClimeCo estimated costs associated with various aspects of project setup and implementation for an average 50 ha typical forest carbon project following the 2024 BC Forest Carbon Offset Protocol. The costs will be approximately $410,500 in the project's first two years. These costs cover most project development activities, forest inventory, project management and administration tasks, verification audits' fees, registration and issuance fees with the crediting companies.

Given the costs involved, landowners in the Upper Clearwater Valley would require substantial financial resources to support a forest carbon project, particularly given the area's limited size and its low-to-medium deforestation risk due to ongoing conservation efforts. High setup costs, uncertain long-term profitability, and modest revenue projections make initial investment challenging. Expanding the project by incorporating neighbouring forest fragments offers a more feasible alternative. This option is viable considering that the study area is already a protected forest owned by three entities: Thompson Rivers University, Edgewood Blue, and The Land Conservancy, and that there are other landowners of small-acreage lands interested in carbon sequestration protection and enhancement.

The aggregation of multiple initiatives into a single, progressively expanding project maximizes carbon sequestration potential (BC Ministry of Environment and Climate Change Strategy, 2022). This structure reduces transaction costs, investment risks, and uncertainties for individual participants, while streamlining the approval process by allowing simultaneous validation of multiple instances (Cline, 2024; Ministry of Environment and Climate Change Strategy, 2024). Therefore, an aggregated carbon project is one of the best alternatives presented in the BC Offset Protocol for a collective of landowners who pursue the implementation of a financially feasible carbon project.

The project scale is crucial for financial success. ClimeCo (2024) recommends aggregating forest carbon offset projects to at least 300 hectares, particularly when 50% of the forest faces a risk of clearing, as this can accelerate revenue generation and profitability. Larger areas (e.g., 450 ha) are more likely to recover investments and yield substantial long-term returns, whereas smaller ones (e.g., 150 ha) may require additional support to remain viable. This study project area of 126 hectares falls below this recommended threshold. Therefore, an expansion to approximately 300 hectares would be necessary to ensure financial viability within the Improved Forest Management category. This larger scale would yield a sufficient quantity of credits to recover initial investments and support positive long-term returns. Eligible expansion areas should be selected based on two primary criteria: a demonstrated history of forest cover over the past 20 years or a credible deforestation threat across 25–50% of their extent, with priority given to lands that also enhance biodiversity corridors and improve carbon sequestration potential.

Despite the current conditions in the study area being unsuitable for a viable forest carbon project, the forest possesses significant carbon sequestration potential. Furthermore, the conservation and management efforts implemented by the land managers position the area as a strong candidate for an aggregated project in the medium term. These characteristics present an opportunity to pursue ecosystem-based approaches beyond the current privately protected area, strengthen carbon sequestration and enhance the forest's ecological functions within the buffer zone of Wells Gray Provincial Park. Proactive strategies that build resilience against climate-related threats, especially wildfires, can safeguard biodiversity, support long-term forest health, and deliver meaningful environmental benefits. Furthermore, a feasible aggregated carbon offset project could exemplify how rural communities can shift land management toward adaptive, service-oriented management, making the region play a vital role in broader climate mitigation efforts.

Quality Requirements for Carbon Crediting

To ensure the environmental integrity of Forest Carbon Offset Projects, there are core elements of carbon credit quality that can be distilled to three criteria:

additionality, permanence and leakage (BC Ministry of Environment and Climate Change Strategy, 2022).

Additionality is the property of a project being additional and is typically assessed once by a crediting program when a proposed project is submitted for approval and registration (Smith, 2025). In practice, additionality is determined by assessing whether the proposed project is distinct from its baseline scenario. If a project is not additional, then the intervention and its baseline scenario are the same (ClimeCo, 2024). The additionality of a project is essential for the quality of carbon credits. If credits are issued to projects that are not additional, then purchasing those credits instead of reducing one's emissions will make climate change worse because total emissions to the atmosphere would be lower if the purchaser had instead reduced their emissions (Broekhof et al., 2024). While additionality is the most essential criterion for assessing credit quality, its determination is inherently predictive (Simpson et al., 2021). Carbon crediting programs must determine the additionality of proposed projects to assess their eligibility for crediting, which involves comparing them to a scenario without revenue from carbon credit sales (Broekhof et al., 2024).

The second core requirement to assess is permanence. Carbon credits must be associated with the permanent avoidance or permanent enhanced removal of GHG emissions (Government of British Columbia, 2024b). One challenge associated with utilizing carbon credits to offset CO2 emissions is the long-lasting impact of these emissions (Ministry of Forests, 2024). While the majority of carbon from a tonne of CO2 emitted today will eventually be removed from the atmosphere, approximately 25% persists for hundreds to thousands of years. Therefore, to effectively compensate for CO2 emissions, carbon credits must be linked to avoided emissions or enhanced removal efforts that are equally permanent (Broekhof et al., 2024).

The issue at hand is that the impacts of certain types of projects can be reversed. A reversal is a decrease in the difference between the project and baseline scenario carbon stocks, for example, due to natural disturbance

(Environment and Climate Change Canada, 2024a). The foremost risk lies with projects that store carbon in reservoirs, such as trees, which may be susceptible to future natural and human disturbances. A prime example of this is a forestry initiative that sequesters carbon in both trees and soils, with the potential to enhance those carbon stores as the forest matures (Gifford et al., 2022). However, if a fire destroys the project's trees or if the trees are cut down to accommodate new development, some or all of the stored carbon may be re-emitted, leading to a reversal (ClimeCo, 2024).

The Federal Offset Protocol (2024) outlines that to ensure permanence of GHG removals: the proponent must prepare a reversal risk management plan. The plan must identify the reversal risk mitigation measures to be implemented. The proponent must monitor the GHG removals for 100 years after the crediting period ends. A portion of offset credits is deposited into the environmental integrity account (EIA). This amount can be decreased if certain reversal risk mitigation measures are implemented (Environment and Climate Change Canada, 2024a).

To protect against the risk of reversal, where the emissions benefit associated with a carbon credit is undone, buffer pools are utilized by registries and developers (Ministry of Environment and Climate Change Strategy, 2024). Contribution to these pools is typically mandatory, and the percentage allocated is based on the reversal risk of individual projects. When a reversal occurs, each impacted credit is replaced by releasing the equivalent number of credits from the buffer pool (Patel, 2025), serving as an insurance mechanism (Broekhof et al., 2024). This approach can cover significant losses if the reserve has enough credits from multiple projects. While buffer reserves effectively address natural disturbance reversals, such as fires or droughts, they face challenges with human-induced reversals, such as intentional timber harvesting (Broekhof et al., 2024).

The increasing scale and frequency of wildfire events raise concerns about the adequacy of these pools. If catastrophic reversals become more common, buffer pools could be depleted (Ministry of Environment and Climate Change Strategy, 2024). This could lead to higher buffer contribution requirements for new projects, increasing costs for developers and potentially reducing the financial viability of certain project types (ClimeCo, 2024; Ministry of Environment and Climate Change Strategy, 2024). Advanced tools such as satellite monitoring and AI prediction models have the potential to enhance the management of wildfire risk and bolster the durability of nature-based projects (Antwi et al., 2023). Innovations in this field closely align with measurement, reporting, and verification technologies. Given the increasing permanence risk associated with nature-based solutions projects, market participants may consider turning to technology-driven removals as an alternative (Patel, 2025).

The third core issue is leakage. This is when actions to reduce harvest (and thus increase forest carbon sinks) in one region indirectly create incentives for third parties to increase harvests (and thus decrease forest carbon sinks) elsewhere (Ministry of Environment and Climate Change Strategy, 2024). Leakage is caused by a shift in market equilibrium, as forest-conservation projects aiming to increase the forest carbon sink reduce local timber supply, leading to increases in market prices for timber and wood-based products, with ensuing pressures on forests outside the project area (Schwarze et al., 2002). However, an increase in timber supply confined to a particular geographical area is likewise susceptible to market-effects leakage, leading to the opposite effect, i.e., potentially reducing harvest pressures outside the area in question (Schulte et al., 2025). Research by the Berkeley Carbon Trading Project on four common leakage methodologies for forest-based projects found that many high-risk projects did not apply leakage deductions. While academic literature indicates leakage rates can range from 10% to 70%, over 59% of the evaluated projects did not account for any deductions (Haya et al., 2023).

ECONOMIC VALUATION OF FOREST CARBON

The economic value of forest carbon can be estimated using prices from established carbon markets, which reflect what buyers are willing to pay for the ecosystem service of carbon sequestration. This analysis uses shadow prices derived from both compliance and voluntary markets, as well as the Social Cost of

Carbon, to assign a monetary value to the sequestration capacity measured in the study area. It is essential to note that this is a non-market valuation exercise, which quantifies the value of an existing ecosystem service and does not constitute a feasibility study for an actual carbon credit project. The stringent requirements for such a project—including establishing a credible baseline, demonstrating additionality, and undergoing third-party verification (BC Ministry of Environment and Climate Change Strategy, 2022), are beyond the scope of this thesis. Instead, by applying these different carbon prices, this chapter highlights the substantial economic value the forest currently provides for both market and non-market beneficiaries.

Compliance Carbon Market

Canada’s GHG Offset Credit System was launched in June 2022, building on the Pan-Canadian Greenhouse Gas Offsets Framework. The system's primary purpose is to generate offset credits for use in the federal Output Based Pricing System (OBPS). Thereby increasing the supply of compliance units for the system through a performance-based system (Clean BC, 2025), reducing compliance costs while creating incentives for voluntary GHG mitigation projects (Government of Canada, 2025b). This system establishes a structured compliance framework that requires companies that exceed their emission limits to either purchase offset credits, submit earned credits, or make direct payments according to the OBPS Compliance Charge (Clean BC, 2025). In 2023, BC announced that the compliance charge was set at $65/tCO_2e for 2023, increasing by $15 each year until it reaches $170 in 2030 (Government of Canada, 2025b). This change has led to a higher demand for legitimate and verifiable carbon offsets generated by forest carbon projects in the province.

Clean BC (2025) reported that the compliance charge rate per tonne of CO_2 equivalent is $95. According to ClearBlue Markets, industry commentary suggests that offset units are already trading at a 10–20% discount to compliance charges, implying forest offsets might be priced around $76–86/tCO_2e in 2025. When a facility reports to be above the emission limit, it has a compliance obligation for each tonne of CO_2e above the emission limit. This obligation may be met through compliance units, such as offset units, consisting of verified units representing emission reductions and removals generated from approved BC carbon offset projects. An offset unit can only be used if its vintage year is three years before the start of the compliance period (Clean BC, 2025).

This compliance market establishes a tangible price for carbon, which can be used as a proxy value to estimate the economic importance of the carbon sequestration service provided by the Upper Clearwater Valley forests. The protected forested area assessed in this research sequesters 666.18 tCO_2e in aboveground and belowground forest biomass. Using the 2025 compliance price of \$95/t CO_2e as a benchmark, the annual carbon sequestration service of this forest can be valued at approximately \$63,287.1. It is important to highlight that this figure reflects a non-market valuation of the ecosystem service. While this valuation illustrates the economic significance of the ecosystem service, it solely assesses the current baseline scenario and does not consider any projected scenarios that could be adjusted for a carbon offset project.

Voluntary Carbon Market

Voluntary markets are a non-regulatory means of directing financial resources to projects that deliver independently verified emissions reductions or other environmental benefits (Government of British Columbia, 2025e). This type of market operates independently of, and can be complementary to, compliance markets (Dunkelman, 2025). Emitters participate in voluntary markets to meet internal carbon reduction goals, achieve environmental, social, and governance targets, fulfill customer contracts, address climate concerns, or offset emissions to comply with green bonds and sustainability-linked debt agreements (Olexiuk et al., 2024). The world's voluntary carbon market grew substantially in 2025, hitting 95 million in the first six months of 2025, the highest total recorded for a half-year. This is fueled by record credit retirements, a focus on integrity, and increased interest in carbon removals compared to traditional avoidance credits (Saptakee, 2025). More importantly, total retirement value increased 32%, indicating buyers are paying more for the right ones (Sylvera, 2025).

Nature-based projects like Afforestation, Reforestation, and Revegetation (ARR) are attracting premium prices. ARR credits sell for 24 USD per ton in the primary market. These credits only make up 3.7% of total retirements, indicating high demand but limited supply (Sylvera, 2025). This adjustment in the price is causing developers to increase high-quality nature-based removal projects; however, land access, cost, and long verification timelines hinder expansion (Saptakee, 2025). The carbon market is demonstrating strong and growing demand for high-quality Improved Forest Management (IFM) credits, with current credit prices around 25 USD and projections reaching over 73 USD by 2035, driven by increased use and declining emissions (Sylvera, 2025).

Investors prioritize IFM projects that are legally protected for permanence by the local community, where proper and culturally appropriate engagement with predominantly Indigenous and small landholder communities has been proven to increase additionality (Smith, 2025). Their participation and action in the project showcase their preference for conservation over other extractive activities. Keeping these communities informed and engaged fosters their support, which is crucial for ensuring the permanence of forest assets that can span decades to centuries (Saptakee, 2025; Smith, 2025).

The trends in the voluntary market highlight a growing premium placed on high-integrity, community-managed forest conservation. This market context provides a useful reference price to quantify the ecosystem service of carbon sequestration. For the already protected forested area in the Upper Clearwater Valley, which sequesters 666.18 tCO_2e, applying the voluntary market price of \$24/t CO_2e yields a valuation of \$15,988.32. This calculation serves to contextualize the scale of the natural asset within the voluntary market framework. It is essential to interpret this not as potential revenue, but as an expression of the carbon sequestration benefit the forest currently provides. This "non-captured" value highlights the community's existing contribution to global climate mitigation, a service currently provided without financial compensation, underscoring the importance of its conservation.

Social Cost of Carbon in Canada

The ecosystems provide vast climate benefits through carbon storage and ongoing sequestration in the forest biomass. These climate benefits provide an additional quantifiable value to local and global communities, called the social cost of carbon. The Social Cost of Carbon (SCC) in Canada estimates the present value of future global damages caused by emitting one additional tonne of carbon dioxide into the atmosphere. This estimate relies on models that simulate the interactions between greenhouse gas emissions, climate change, and the global economy, often extending to the year 2300. The resulting damage estimations are then converted into monetary values to reflect the cost of each additional tonne of emissions (Government of Canada, 2023).

Canada has adopted the methodological framework developed by the United States Interagency Working Group (IWG) to calculate SCC, with modifications fitting Canadian inflation and currency. A key feature of Canada's SCC is the use of global damage estimates, acknowledging the interconnected nature of climate change impacts, regardless of where emissions occur (Government of Canada, 2023). Discount rates are applied to translate future costs or benefits into present-day values; they reflect how much the future will be valued compared to the present. Then, a higher rate means we value future impacts less, and a lower rate means we value them more (U.S. Environmental Protection Agency, 2023). Canada uses 1.5%, 2%, and 3% discount rates to capture a range of perspectives on how society might value future climate damages (Government of Canada, 2023).

One of the primary advantages of using the SCC is that it provides a scientific and economic estimate of the actual cost of emissions, given the scale of the variables involved in the calculations. This estimate has been used for decision-making that would lead to changes in GHG emissions, such as in the context of federal impact assessments, specifically, as part of the cost-benefit analysis of regulatory proposals (Government of Canada, 2023). The SCC also faces several criticisms. Its estimates are susceptible to small changes in assumptions about future socioeconomic pathways, climate sensitivity, and especially the discount rate, which determines how much future damages are valued today, raising concerns about uncertainty and transparency (Evans et al., 2017; Kotchen, 2016; Simpson et al., 2021).

From this perspective and considering the previously presented prices of the CO_2eq in Canada's compliance and voluntary market, it is relevant to compare the current amounts traded and used to undertake environmental projects at different scales. As of 2025, this results in a central SCC estimate of \$271/ tCO_2e. Each economic valuation has specific assumptions and scopes that need to be evaluated to determine its suitability for use, particularly for the study area of this research. Table 4.3 summarizes the three economic valuations used in this research and their specific implications.

Category	Carbon Price (CAD)	Purpose	General Implications
Voluntary Market	\$15-90 /tCO_2e (e.g., IFM credits as of 2024–2035 projection)*	Supports carbon offset projects (e.g., forestry, renewables)	Enables private actors to offset emissions voluntarily; pricing is variable and project-dependent.
Compliance Market	\$80 /tCO_2e; rising \$15/year to reach \$170 by 2030	Meets regulatory obligations under federal/provincial systems	Creates financial incentive to reduce emissions; affects fuel costs and industrial operations.
Social Cost of Carbon	\$261/tCO_2e(central estimate at 2% discount rate)**	Used in the cost-benefit analysis of federal regulations	Reflects the long-term climate damage per tonne of CO_2; informs climate policy design, not trading.

Table 4.3 Comparison of the carbon price in Canada in the voluntary and compliance market, and the social cost of carbon

As indicated in Table 4.3, carbon credit prices and the social cost of carbon (SCC) are distinct. The price in a compliance market is determined primarily by the stringency of the regulation it serves, such as a government-set carbon tax or emissions cap. Conversely, voluntary market prices are shaped by dynamic factors, including buyer demand for high-integrity credits, project-specific quality, and co-benefits such as biodiversity conservation. The SCC, in contrast, is an estimated metric of the global economic damages associated with emitting one tonne of carbon, representing the value of damages foregone by reducing emissions. While the SCC is useful for informing long-term policy goals by quantifying the broader societal cost of carbon, compliance and voluntary market prices are practical, actionable signals. Consequently, carbon market prices are reference points for assessing whether carbon pricing or mitigation efforts are ambitious (OECD, 2023). These market prices incentivize immediate emissions reductions and serve as reference points for assessing the ambition of current mitigation efforts (World Bank, 2023).

From another perspective, some climate impacts can have complex socioeconomic implications that cannot be translated into monetary terms. Civil conflict, socioeconomic inequity and human migration, for example, fall into this category of “identifiable but hard to quantify” impacts (Evans et al., 2017). This represents a critical bias for policymakers and budgeting managers, as climate change-related projects will likely compete neck-and-neck with basic-needs projects once their economic valuation has been run at a larger scale that generalizes geographically socioeconomic needs (Hashemi, 2024).

The use of a global SCC may not reflect Canada's domestic priorities and could be politically controversial if used to justify stringent national regulations without clear domestic benefits (Kotchen, 2016; World Bank, 2023). These limitations have led to the criticism that the SCC estimations are skewed since it is easier to see mitigation costs than the benefits of not emitting (Evans et al., 2017). In this sense, SCC is only a relevant tool to determine the economic value of forested areas with high carbon capacity in the context of regional, provincial or national policymaking. Despite its significance for high-level environmental programs, using SCC for calculating the economic value of the private forested areas in the Upper Clearwater Valley is not appropriate since local decisions would not be made based on this high value but on the carbon market price that eventually will represent a tangible transaction for landowners.

THE IMPACTS OF FOREST CARBON COMMODIFICATION

Even though offsetting programs often cover several GHG reduction practices, to allow project managers to find a combination of practices aligned with their values, which increases local community engagement (ClimeCo, 2024; Emerick, 2024; Smith, 2025; Wilson, 2019), implementing them typically involves the loss of economic opportunity for some stakeholders in the regional area due to a decrease and/or elimination of timber harvesting. In the long term, the project creates an offsetting amount of direct economic benefits for stakeholders and the local community due to property planning and management, project monitoring, project activities and increases recreational activity opportunities (Wilson, 2019).

Nevertheless, the development of carbon markets has met challenges in Canada. Shrestha et al. (2022) identify questions of leakage, permanence, additionality, and monitoring design as issues that continue to challenge the expansion of carbon offsetting within global emissions trading systems. Permanence concerns whether carbon can be securely stored over time, while additionality questions whether the project would have occurred without carbon credit funding (Van Kooten et al., 2015). Attributability examines whether observed emissions reductions are directly due to the project rather than external factors, and leakage refers to the possibility that emission reductions in one area may cause increases elsewhere (Cline, 2024; Ministry of Environment and Climate Change Strategy, 2024; Van Kooten et al., 2015; Wilson, 2019). These concepts represent key risks that carbon offset project developers must assess to avoid overstating carbon sequestration capacity.

Critics argue that carbon markets enable large polluters to delay real emissions reductions, raising questions of environmental justice and market integrity (Emerick, 2024), carbon ownership, and social license for projects (Van Kooten et al., 2015). These concerns have become notorious as the use of carbon offsets has grown, with accusations of greenwashing against companies and the government. In this case, greenwashing refers to a situation where the climate benefits that a particular company claims do not match the reality, since they have chosen risk over-crediting projects (Gabbastiss et al., 2023). To clarify these claims, in 2023, the carbon-credit-rating company Sylvera, found that purchasing offsets was associated with actual emissions reductions, arguing that, in addition to the standards, there is a supporting system of auditors who prevent over-crediting (Sylvera, 2023).

In a systematic account of offset policies, Hahn and Richards (2013) argue that offset programs can potentially reduce the costs of achieving environmental targets. This is difficult to establish in practice due to the vast array of options for trading sequestration services. Antwi et al. (2023) suggest that more investment in research is needed to address the challenges associated with assessing and reporting on climate change adaptation and mitigation practices, which include strengthening the link between forest practices and carbon accounting at provincial and territorial scales. Nonetheless, the value of forests in mitigating climate change impacts remains a continued area of research and economic interest (Gullbrandsen and Wettestad 2022; Shrestha et al. 2022), and recent policy decisions are now ensuring that the carbon reductions are real and properly accounted for.

CONCLUSION

The current configuration of the private protected forest in the Upper Clearwater Valley does not yet support a financially viable forest carbon offset project due to its limited area, unless an aggregated project with neighbouring forest patches is implemented. Expanding the project beyond the lands owned by Thompson Rivers University, Edgewood Blue, and The Land Conservancy could shift the carbon scenario, favouring the carbon storage and sequestration rates that the carbon market demands. The initiative could deliver various co-benefits if conservation-minded landowners across the valley collaborate to develop an aggregated project. These include enhanced ecosystem services, increased resilience to climate change, and meaningful contributions to local well-being through job creation, economic development, and improved quality of life for surrounding communities.

Rural communities in BC, such as the Upper Clearwater Valley, whose members are seeking sustainable practices that maintain and enhance ecosystem services, require capacity-building and support to navigate the technical risks, regulatory, and financial aspects of carbon projects. Due to the high risks involved, a carbon project with these characteristics requires support from land managers and district and regional governments. Long-term commitments are essential to ensure the project's success, particularly regarding land use planning strategies that will not adversely affect the surrounding area. The incorporation of crown lands and actively engaging the local community in these initiatives can provide crucial alternative support for the project.

This research applied a non-market valuation to the carbon sequestration service provided by the Upper Clearwater Valley forest. The analysis used three distinct metrics: the provincial compliance price, the voluntary market price, and the SCC. The results demonstrate that the value of this ecosystem service under the current conservation scenario is highly dependent on the chosen metric. The compliance and voluntary market prices provide a conservative, market-based estimate reflective of current policy and corporate demand. In contrast, the SCC, which aims to capture the global economic damages avoided by emissions reductions, assigns a significantly higher value to the same sequestration service. This disparity highlights that the forest's carbon sequestration represents a substantial, non-marketed benefit, whose estimated monetary value varies depending on the perspective of the beneficiary, whether it is a regulatory market, a voluntary buyer, or global society.

This research demonstrates that the carbon sequestration capacity of the study area provides a valuable, yet non-marketed, ecosystem service. By applying different valuation metrics, the analysis quantifies this service in monetary terms, revealing a substantial annual value that contributes to the natural capital of the Upper Clearwater Valley. While this study did not conduct a carbon offset project feasibility analysis, which would require establishing a modelling additionality, the valuations presented provide an indispensable foundation for such future work. Ultimately, this analysis underscores that the value of these forests extends far beyond traditional timber, highlighting the vital role of ecosystem service valuation in guiding sustainable land-use decisions and climate policy for rural communities.

REFERENCES

An, Z., Bork, E. W., Duan, X., Gross, C. D., Carlyle, C. N., & Chang, S. X. (2022). Quantifying past, current, and future forest carbon stocks within agroforestry systems in central Alberta, Canada. *GCB Bioenergy*, *14*(6), 669–680. https://doi.org/10.1111/gcbb.12934

Antwi, E. K., Burkhardt, H., Boakye-Danquah, J., Doucet, T., & Abolina, E. (2023). Review of climate change adaptation and mitigation implementation in Canada's forest ecosystems part I: Reporting, science, and institutional/governance supporting practices in Canada. *Environmental Reviews*, er-2022-0130. https://doi.org/10.1139/er-2022-0130

BC Ministry of Environment and Climate Change Strategy. (2022, June). *BC Offset Protocol Policy*. Government of British Columbia. https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/protocol/bcs_offset_protocol_policy.pdf

Citizens Climate Lobby. (2023). *Canada's Federal Carbon Pricing System*. https://community.citizensclimate.org/resources/item/19/382?

Clean BC. (2025). *BC OBPS PROGRAM AND REPORTING GUIDANCE* (Province of BC Climate Change). https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/obps/guidance/bc_obps_guidance.pdf

ClimeCo. (2024). *Carbon Project Feasibility Assessment* [Coastal Douglas-fir Conservation Partnership (CDFCP)]. https://www.cdfcp.ca/wp-content/uploads/2024/06/Carbon-Feasibility-Report-Loc-Gov-v2.0-Final.pdf?

Connell, D. J., Hall, J., & Shultis, J. (2017). Ecotourism and forestry: A study of tension in a peripheral region of British Columbia, Canada. *Journal of Ecotourism*, *16*(2), 169–189. https://doi.org/10.1080/14724049.2016.1255221

Council of Canadian Academies. (2022). *Nature-Based Climate Solutions*. CCA Reports; Environment and Climate Change Canada. https://cca-reports.ca/reports/canadas-carbon-sink-potential/

District of Clearwater. (2021). *Economic Development Strategy* (No. Final Report; p. 179). Province of British Columbia. https://www.districtofclearwater.com/wp-content/uploads/2021/03/Community-Economic-Development-Startegy-Final-2021-01-211.pdf

Dunkelman, A. (2025, April 7). Canada's Carbon Markets: A Patchwork of Pricing Systems. *ClearBlue Markets*. https://www.clearbluemarkets.com/knowledge-base/canadas-carbon-markets-a-patchwork-of-pricing-systems

Emerick, D. (2024, December 30). Why Carbon Offsets Won't Work. *ESG The Report*. https://esgthereport.com/why-carbon-offsets-wont-work/

Evans, S., Pidcock, R., & Yeo, S. (2017, February 14). Q&A: The social cost of carbon. *CarbonBrief*. https://www.carbonbrief.org/qa-social-cost-carbon/

Gabbastiss, J., Dunne, D., Chandrasekhar, A., Dwyer, O., Lempriere, M., Quiroz, Y., Tandon, A., & Viglione, G. (2023, September 24). In-depth Q&A: Can 'carbon offsets' help to tackle climate change? *CarbonBrief*.

Gifford, R., Brown, C., Baron, C., Clement, D., Melnychuk, N., Nelson, H., Sales, L., & Spittlehouse, D. (2022). *British Columbia Chapter in Canada in a Changing Climate* (Regional Perspectives Report, p. 76). Government of Canada. https://publications.gc.ca/collections/collection_2023/rncan-nrcan/M174-25-2021-5-eng.pdf

Government of British Columbia. (2024, August 6). *Forest Carbon Initiative*. Addressing Climate Change with Nature. https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/natural-resources-climate-change/natural-resources-climate-change-mitigation/forest-carbon-initiative

Government of British Columbia. (2025, June 24). *Carbon Neutral Government carbon offset portfolio*. Environmental Protection and Sustainability. https://www2.gov.bc.ca/gov/content/environment/climate-change/public-sector/offset-portfolio?

Government of Canada. (2017, December 12). *Paris Declaration on Carbon Pricing in the Americas*. Environment and Natural Resources. https://www.canada.ca/en/services/environment/weather/climatechange/canada-international-action/international-collaboration/paris-declaration-carbon-pricing-americas.html?

Government of Canada. (2023, April 20). *Social Cost of Greenhouse Gas Estimates – Interim Updated Guidance for the Government of Canada*. Environment and Natural Resources. https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/social-cost-ghg.html

Government of Canada. (2025, February 28). *Canada's Greenhouse Gas Offset Credit System*. Canada.Ca. https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system.html

Haley, D., & Nelson, H. (2007). Has the time come to rethink Canada's Crown forest tenure systems? *The Forestry Chronicle*, *83*(5), 630–641. https://doi.org/10.5558/tfc83630-5

Hashemi, M. (2024, October 16). How the 'social cost of carbon' can hide economic inequalities and mask climate suffering [Queen's Gazette]. *The Conversation*. https://www.queensu.ca/gazette/stories/how-social-cost-carbon-can-hide-economic-inequalities-and-mask-climate-suffering#:~:text=To%20a%20national%20policymaker%2C%20an%20almost%20zero,resources%20to%20the%20fight%20against%20climate%20change.

Kotchen, M. (2016). *Which Social Cost of Carbon? A Theoretical Perspective*. National Bureau of Economic Research. https://doi.org/10.3386/w22246

Krenke, A. N., Ptichnikov, A. V., Shvarts, E. A., & Petrov, I. K. (2021). Assessments of the Forest Carbon Balance in the National Climate Policies of Russia and Canada. *Doklady Earth Sciences*, *501*(2), 1091–1095. https://doi.org/10.1134/S1028334X21120060

Ministry of Environment and Climate Change Strategy. (2024, April 18). *British Columbia Forest Carbon Offset Protocol*. https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/protocol/bc_forest_carbon_offset_protocol.pdf

Ministry of Forests. (2024). *Forest Carbon Initiative—Province of British Columbia*. Www2.Gov.Bc.Ca. https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/natural-resources-climate-change/natural-resources-climate-change-mitigation/forest-carbon-initiative

Ministry of Forests, Lands and Natural Resource Operations. (2011). *CROWN LAND: Indicators & Statistics Report* (No. 2010). Province of British Columbia. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/natural-resource-use/land-water-use/crown-land/crown_land_indicators__statistics_report.pdf

OECD. (2023). *Effective Carbon Rates 2023: Pricing Greenhouse Gas Emissions through Taxes and Emissions Trading*. OECD. https://doi.org/10.1787/b84d5b36-en

Olexiuk, P., Sadikman, J., Guindi, S., & Boyd, M. (2024). *Navigating Canada's evolving carbon markets* (2024 OSLER LEGAL OUTLOOK). Osler Law Firm. https://www.osler.com/en/insights/reports/2024-legal-outlook/navigating-canadas-evolving-carbon-markets/

Riany, F., Welder, L., Grant, N., Kellou, D., Klonne, U., & Hare, B. (2024). *The role of northern forests in limiting warming to 1.5°C*. CLIMATE ANALYTICS.

Saptakee, S. (2025, July 3). *Carbon Removal in 2025: Are You Investing in the Right Climate Credits?* [Carboncredits.com]. https://carboncredits.com/carbon-removal-in-2025-are-you-investing-in-the-right-climate-credits/

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., … Trisos, C. H. (2021). A framework for complex climate change risk assessment. *One Earth*, *4*(4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

Smith, L. (2025, July 6). High-Quality Forest Management Emerges as a Cornerstone of Carbon Markets [CLEARBLUE MARKETS]. *Offsets*. https://www.clearbluemarkets.com/knowledge-base/high-quality-forest-management-emerges-as-a-cornerstone-of-carbon-markets?u

Sylvera. (2023). *Carbon credits: Permission to pollute, or pivotal progress?* https://www.sylvera.com/reports/carbon-credits-and-decarbonization

Sylvera. (2025). *Carbon Market Data* (Nos. 2025-Q1). Sylvera. https://www.sylvera.com/discover/carbon-market-data

U.S. Environmental Protection Agency. (2023). *EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances* (No. EPA-HQ-OAR-2021-0317). EPA. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf

VERRA. (2025). *Grouped Projects*. Verified Carbon Standard. https://verra.org/programs/verified-carbon-standard/grouped-projects/

Wilson, R. (2019). *DARKWOODS FOREST CARBON PROJECT* [Sustainable Development Verified Impact Standard]. Nature Conservancy of Canada.

WORLD BANK GROUP. (2023, April 1). *State and Trends of Carbon Pricing Dashboard*. Carbon Pricing. https://carbonpricingdashboard.worldbank.org/compliance/factsheets?instrument=ETS_CA_BC

Chapter 5. Conclusion

THE ASSESSMENT OF PRIVATE FOREST CARBON FOR POLICY-MAKING

Carbon stock modelling at the landscape scale demonstrates that national-scale models have underestimated carbon density (Drever et al., 2021; Walker et al., 2022). Globally, governments rely on carbon models with a maximum resolution of 250 m due to their suitability for provincial-level decision-making (Ploton et al., 2020). Nevertheless, regional and municipal governments cannot access finer information on current carbon storage and sequestration rates to plan land use changes that aim to adapt communities to the adverse effects of climate change on vegetation and soil productivity, climate regulation, and water provision (Carrie Moffatt, 2020). Based on these findings and the constant struggle to find ways to manage the impacts of the climate change crisis, regional and municipal governments should start investing in and adopting carbon models at a fine scale, which could at least provide a starting point to prioritize areas where deeper assessments can be conducted (Bubnicki et al., 2024; Meyer et al., 2019; Sothe et al., 2022). This study exemplifies this application. LiDAR-assisted biomass modelling for high-priority carbon areas like the Interior Cedar-Hemlock (ICH) zone is paramount to create more accurate provincial carbon budgets and identify carbon hotspots.

While accurately estimating carbon storage is essential for quantifying existing climate mitigation assets, as most of the national models have done, the measurement of carbon sequestration enables governments to achieve and scale their climate goals. The understanding of how sequestration rates transforms a static carbon stocks inventory into a dynamic management serve as a tool to allow policymakers to project progress toward carbon neutrality or reduction targets, evaluate the effectiveness of reforestation and improved forest management programs, and make strategic investments in the landscapes with the highest drawdown potential (Antwi et al., 2023; Smyth et al., 2023). For governments and climate action project managers, both carbon storage and sequestration metrics are critical to understand the forests' accumulation potential, to ensure that actions can be taken to enhance the land's capacity to serve as a growing carbon sink (Sharma et al., 2023).

Historically, policies have often prioritized the protection of old-growth forests since their scientific study was extensive in the previous century, but it is crucial to extend this focus to include and incentivize the safeguarding of maturing secondary forests as well (Mina et al., 2022). Research indicates that private mid-successional forests are not merely "future old-growth" but are, in fact, important carbon reservoirs currently exhibiting high sequestration rates (Schuldt et al., 2023; Yang et al., 2023). These areas should be regarded as essential conservation priorities. It is essential to introduce new regulations and promote the value of mid-successional forests for their carbon storage and sequestration benefits, effectively making them a key component of BC's climate mitigation strategy.

The recognition of forested areas on private lands is a valuable asset for conservation, watershed protection, and wildfire mitigation. Despite this, relying on private management to meet government objectives can pose challenges in terms of supervision and resource management (Lamb et al., 2021). Thus, it is vital to expand the conservation financing mechanisms specifically to support the purchase of conservation covenants or the acquisition of private lands in crucial connectivity areas (Miller et al., 2012), such as the rangelands north of the study area, to facilitate the establishment of the proposed forest corridors.

The findings of this research emphasize that the social value of forest carbon in the Upper Clearwater Valley is inherently tied to the motivations and needs of diverse stakeholders who interact with these forest fragments on private and crown lands. Interviewees clarified that forests are not only seen as tools to mitigate and adapt to climate change through carbon sequestration but are also part of the region's economic and cultural roots. At the same time, their insights underscore the challenges associated with forest fragmentation management in a very land-use diverse valley. This dual role highlights the necessity of adopting management approaches that balance ecological conservation with long-term livelihood security (Howe et al., 2014).

Stakeholders expressed concern that provincial-level decision-making does not always translate into local benefits for the valley. Therefore, private lands emerged as the most viable starting point for implementing forest carbon projects because of their flexibility, the strong sense of stewardship among some landowners, and precedents such as the FireSmart program. This offers a chance to add carbon sequestration goals to already locally accepted programs, strengthening community resilience while simultaneously contributing to climate change mitigation. In fact, the benefits of greenhouse gas mitigation are greater for properties that have been involved in the FireSmart program, particularly when stands were rehabilitated 30 to 40 years before a wildfire occurred (Metsaranta et al., 2023). This demonstrates that the existing protected forest can serve as an exemplary model of forest management for the residents of the valley.

The role of forestry and tourism in the region illustrates that climate solutions could be efficiently incorporated into economic activities. For instance, low-impact tourism operators using the Wells Gray Provincial Park buffer area have demonstrated that conservation and recreation can be mutually reinforcing. From their own legal and operational limitations, the local community forest corporation claims to be committed to sustainable harvesting practices. If these commitments materialize, the forestry company could open a window for linking conservation outcomes to working forest models. The Forest and Range Practices Act (FRPA), guided by the Community Forest Agreements, provides the forestry legal framework, which establishes operational limitations and mandates sustainable forest management plans. These regulations are instrumental to transform harvesting into carbon sequestration enhancement plans within the rural development framework.

Another critical dimension emerging from this research is the need for greater engagement from regional authorities. Stakeholders consistently identified gaps in communication and collaboration, suggesting that a more participatory governance model is necessary, given the valley's high value for tourism around Wells Gray

Provincial Park. For the Thompson-Nicola region, this indicates that future policy should involve establishing programs for carbon and climate-related projects, to support communities, such as those in the Upper Clearwater Valley, to shape project parameters and long-term management strategies. The Thompson-Nicola Regional District (TNRD) owns Official Community Plans (OCPs) and a Regional Growth Strategy (Thompson-Nicola Regional District, 2025), where they acknowledge the need for collaboration. Despite this, significant involvement of the community in carbon-related projects has not been implemented yet**.** Carbon-related strategies could reward private stewardship practices through tax incentives, conservation easements, or community carbon funds to reinforce the emergence and continuity of such projects alongside community development.

While the ecological and social benefits of expanding forest carbon projects in the valley are evident, the research also demonstrates that current configurations of protected land are insufficient to generate viable carbon credits in the short term. The project becomes financially feasible when its scope expands beyond the already private protected areas. This creates challenges and opportunities for BC's policy framework. Even though the provincial government have launched programs such as CleanBC Community Fund (Government of British Columbia, 2025a) and the Forest Carbon Initiative (Ministry of Forests, 2024) explicitly supports large projects that reduce emissions through various streams. These programs could better be tailored and promoted in rural, tourism-dependent communities like the Upper Clearwater Valley. In addition, there are multiple limitations for small-scale projects within the current carbon market structure and a lack of capacity to navigate these types of projects' requirements. Consequently, proactive support from agencies such as the TNRD is needed to help communities like Clearwater navigate the application process.

Policy implications include integrating crown lands into carbon sequestration initiatives. While private lands are the immediate focus, involving provincial crown lands can enhance project stability and continuity. To support this, the municipality of Clearwater should revise its Community Economic Development Strategy to include principles that encourage private landowners to conserve wooded areas and other ecologically significant vegetation—an element currently missing from the strategy (District of Clearwater, 2021). The municipality could also engage in provincial integrated resource planning to foster collaboration across public and private lands, enhancing ecological connectivity and generating shared economic benefits through carbon markets. The fluctuations in carbon credit valuations driven by market demand and regulatory shifts add complexity to multi-level government programs. These dynamics highlight the need for provincial intervention to stabilize rural carbon projects through risk-sharing mechanisms.

Finally, the broader implication of this research is that rural carbon projects like the one proposed in the Upper Clearwater Valley represent more than a mechanism for reducing emissions. They can act as catalysts for community development, job creation, and the diversification of rural economies. By aligning local stewardship practices with provincial and national climate policies, such projects provide a model for integrating environmental and socioeconomic objectives. The success of these projects will depend on multi-level governance approaches that combine the flexibility of local decision-making with the support of provincial institutions.

LIMITATIONS OF THE RESEARCH

The tree-inventory-based model proved to be the most accurate method for estimating carbon sequestration, primarily due to its in-situ collection of detailed forest metrics—including land use, total and live tree height, crown base height, crown width, percent crown missing, crown health, and crown light exposure. These inputs allow the model to more effectively capture the structural and functional characteristics of the forest in the study area. However, its accuracy is limited by the scope of the pilot sample, which covered only 10% of the total study area.

The remote-sensing-based model had a moderate level of accuracy due to several errors inherent to spatial analysis standard procedures, such as individual tree georeferenced mismatches from GPS field data to individual tree LiDAR point clouds and, therefore, segmentation errors. Since LiDAR data does not allow for modelling DBH, a regression model was run to predict DBH for all the trees identified in the LiDAR data based on field data. The model's foundation is also contingent upon the accuracy of the DBH regression model derived from field data. Any bias or error in this initial step is propagated through the entire biomass estimation process. This process step led to errors in the final model added from DBH prediction model.

Furthermore, the LiDAR-derived metrics, while detailed, may not fully capture the complex three-dimensional structure of the forest or species-specific allometric relationships, potentially leading to generalization errors. The tree detection accuracy of the model using LiDAR data delivered values of forest biomass that need to be refined to estimate a more accurate carbon sequestration capacity. Finally, the stark contrast in variable importance between the two slopes suggests that the model is not readily transferable, limiting its application to other areas without localized recalibration. The fine scale of this spatial analysis and the particularity of the machine learning methods used to process the LiDAR data limit our approach's applicability in other regions regarding its transferability and scalability.

The carbon sequestration estimates generated by both models are limited to the geographic boundaries of the study area and reflect the forest’s health and structural characteristics at the time of data collection. The analysis captures current carbon storage and sequestration capacity, assuming the forest retains its existing height and age distribution. Stand-level assessments require extensive plot data to develop reliable empirical models for biomass estimation. Thereby, this research carbon sequestration model is only applicable to mixed-wood forests in early successional stages within the Upper Clearwater region that share similar structural attributes and are subject to comparable management practices and environmental pressures.

The conclusions regarding the socioeconomic value of forest carbon are based solely on input from a subset of stakeholders in the Upper Clearwater Valley, drawn from a broader spectrum of landowners, land managers, and decision-makers. Interviewees were intentionally selected for their roles within strategic community, academic, and sociopolitical groups that influence land use decisions in the region. Their perspectives ranged from strong advocacy for complete forest preservation, to support for landscape-level interventions, and to active forest management aimed at maximizing resource use. Due to the scale of the study, voices from other potentially affected groups, such as Indigenous communities, recreational users, and small-scale landowners not contacted but willing to manifest their mind were absent.

Additionally, most interviewees stated that some private landowners in the valley may not be willing to share their insights due to the exploratory nature of this research or because they have already expressed their preferences for the type of use they want to make of their lands. To conduct broader-scale research on the viability of creating a proper forest corridor or private reserve, consulting more private landowners whose lands are suitable for inclusion in the managed area, based on a previous robust feasibility assessment, would be necessary.

The economic feasibility assessment of the hypothetical forest carbon offset project in the valley was conducted based on certain assumptions outlined in Chapter 4, which were derived from a reference case study analyzed by consultants at ClimeCo. These assumptions align with the BC Protocol for Forest Carbon, the consultants' expertise, and the current administrative costs established by recognized private companies and the BC government. It is essential to emphasize that the recommendations regarding the feasibility of the project depend on multiple factors, including the project size, type, anticipated carbon sequestration timeline, the proportion of wood that can be harvested within the project's framework, and the level of deforestation threat considered in the assessment. This information should serve as a foundational reference point for making informed decisions about developing a tailored project that reflects the socioeconomic and ecological characteristics of the land involved.

FUTURE RESEARCH

Accurate estimates of stored carbon and understanding sources and sinks can improve the accuracy of carbon flux models and thus lead to better projections of climate change and impacts. In this sense, above-ground biomass estimates are the central basis for carbon inventories and most international negotiations in carbon trading schemes. Carbon trading markets require long-term information on carbon stocks, particularly on the above-ground ‘live’ biomass component, as this is the most dynamic, changing and manipulable component of all the biomass pools (Kumar & Mutanga, 2017). This is the ‘merchantable’ component of biomass.

Sample size can impact statistical analyses. Therefore, further analysis for the same area could consider a larger number of plots needed for deriving stable results. The plots should be sufficiently large to include enough trees, which shows the stand structure. High-accuracy models to predict above-ground biomass using LiDAR data from several studies comprehend plot sampling series of 2-3 years (Assmuth et al., 2021; Awaya & Takahashi, 2017; X. Chen et al., 2024; Sothe et al., 2022), which provides a wide timeframe for collecting data and capturing changes in the forest structure over a short time. This could represent opportunities to accurately estimate carbon storage and sequestration under climate change threats. This will enrich the model's training data and reflect patterns in the distribution of species clusters and the distribution of age and height in the forests.

To enhance the model's accuracy using LiDAR data, separating areas with different tree species clusters would be essential to improve the biomass mapping [19]. Individual analyses of different species’ clusters improve the prediction accuracy of forest variables (Awaya & Takahashi, 2017; Cao et al., 2014; Liu et al., 2017). Most LiDAR-based studies separately analyzed the biomass of conifer, broadleaved, or mixed forests. The performance of LiDAR data for biomass estimation is probably different among forest types (Cao et al., 2014). Minimizing the influence of DTM accuracy is important to evaluate the performance of LiDAR point data for stand volume estimation (Awaya & Takahashi, 2017).

Given the socioeconomic valuation of carbon sequestration results, the expansion of the forest through a community-based corridor project across several private lands appears feasible. Non-interviewed landowners in the valley are already engaged in conservation initiatives led by The Land Conservancy, Edgewood Blue, and Thompson Rivers University. This creates a foundation for broader collaboration. Building on the existing network of landowners practicing fire-smart management, such a project could indirectly enhance carbon sequestration while reducing wildfire risks. To develop improved vegetation management strategies aligning with fire protection and carbon storage objectives would strengthen the groundwork for a robust, community-based conservation initiative.

The first step in advancing such a project is to conduct a social mapping of the valley. This process would identify: (1) the distribution of groups based on their willingness to participate; (2) forest patches with higher carbon sequestration potential and fire resistance; (3) existing social networks; (4) perceived power dynamics; and (5) areas of exclusion arising from social or land-use conflicts. Interview insights can inform this initial mapping by highlighting additional factors not addressed in the present study (Buckingham et al., 2018; Cusens et al., 2023; Sothe et al., 2022). Furthermore, involving representatives from other stakeholder groups in the mapping process would ensure that higher-level governments know community intentions and priorities, to foster alignment between local conservation efforts and broader policy frameworks.

Under this scenario, incorporating the Simpcw First Nation into social mapping is essential. This would also enable the integration of Indigenous knowledge and practices into landscape-based management. By visualizing land use, rights, and community priorities, social mapping can highlight opportunities for issuing new harvesting licenses over Crown lands to the Simpcw that are consistent with Canada’s reconciliation framework. This approach respects Indigenous rights and enhances ecosystem services by aligning traditional stewardship with sustainable resource management (Government of Canada, 2024b). Through this process, social mapping becomes a tool to bridge ecological planning with Indigenous communities' lived realities and priorities.

At the policy level, the federal Offset System supports voluntary greenhouse gas (GHG) reductions beyond business-as-usual practices. This establishes potential for Indigenous-led projects that align with Canada's commitment to the UN Declaration on the Rights of Indigenous Peoples (Government of Canada, 2024b). Forming a Protocol Focus Group for Improved Forest Management on private and Indigenous lands offers incentives for Indigenous participation in project leadership, monitoring, and risk management (Government of Canada, 2024a). In the context of Crown or public lands, social mapping can help ensure projects are consistent with principles of Indigenous rights recognition, provincial authority, and transparent entitlement to offset credits (Cusens et al., 2023).

In addition, the participation of tourism operators and the local community forest is critical to build partnerships that secure the project's long-term success. The Wells Gray Community Forest Corporation community forest could designate ecologically significant areas to remain unharvested, contributing to carbon storage while forming a strategic corridor, supporting wildlife movement and enhancing genetic exchange among vegetation, thereby strengthening forest resilience. Simultaneously, a landscape-based tourism approach will raise awareness of conserving private lands within buffer zones surrounding large protected areas, such as Wells Gray Provincial Park.

Finally, social mapping can also serve as a foundation for identifying opportunities to generate economic income through carbon offset projects. By linking land ownership, management practices, and areas of high carbon sequestration potential, social mapping will determine which properties or community-managed lands can participate in federal or voluntary offset systems. This creates pathways for landowners, Indigenous communities, and local organizations to benefit financially from improved forest management, restoration, or conservation practices that go beyond legal requirements. Linking these economic incentives to community supports long-term project viability and prioritizes conservation efforts are socially inclusive, locally driven, and aligned with broader climate policy frameworks.

REFERENCES

Antwi, E. K., Burkhardt, H., Boakye-Danquah, J., Doucet, T., & Abolina, E. (2023). Review of climate change adaptation and mitigation implementation in Canada's forest ecosystems part I: Reporting, science, and institutional/governance supporting practices in Canada. *Environmental Reviews*, er-2022-0130. https://doi.org/10.1139/er-2022-0130

Awaya, Y., & Takahashi, T. (2017). Evaluating the Differences in Modeling Biophysical Attributes between Deciduous Broadleaved and Evergreen Conifer Forests Using Low-Density Small-Footprint LiDAR Data. *Remote Sensing*, *9*(6), 572. https://doi.org/10.3390/rs9060572

Bubnicki, J. W., Angelstam, P., Mikusiński, G., Svensson, J., & Jonsson, B. G. (2024). The conservation value of forests can be predicted at the scale of 1 hectare. *Communications Earth & Environment*, *5*(1), 196. https://doi.org/10.1038/s43247-024-01325-7

Buckingham, K., Ray, S., Morales, A., Singh, R., Dow, M., Wicaksono, S., Chrysolite, H., Minnick, A., Johnston, L., & Arakwiye, B. (2018, August 22). *Mapping Social Landscapes: A Guide to Identifying the Networks, Priorities, and Values of Restoration Actors*. WORLD RESOURCES INSTITUTE. https://www.wri.org/research/mapping-social-landscapes-guide-identifying-networks-priorities-and-values-restoration

Cao, L., Coops, N., Hermosilla, T., Innes, J., Dai, J., & She, G. (2014). Using Small-Footprint Discrete and Full-Waveform Airborne LiDAR Metrics to Estimate Total Biomass and Biomass Components in Subtropical Forests. *Remote Sensing*, *6*(8), 7110–7135. https://doi.org/10.3390/rs6087110

Carrie Moffatt. (2020, December). Barriers to Climate Action in Municipalities. *BarTalk British Columbia*. https://bartalk.org/article/features/2020-12/barriers-to-climate-action-in-municipalities

Cusens, J., Barraclough, A. D., & Måren, I. E. (2023). Integration matters: Combining socio-cultural and biophysical methods for mapping ecosystem service bundles. *Ambio*. https://doi.org/10.1007/s13280-023-01830-7

District of Clearwater. (2021). *Economic Development Strategy* (No. Final Report; p. 179). Province of British Columbia. https://www.districtofclearwater.com/wp-content/uploads/2021/03/Community-Economic-Development-Startegy-Final-2021-01-211.pdf

Drever, C. R., Cook-Patton, S. C., Akhter, F., Badiou, P. H., Chmura, G. L., Davidson, S. J., Desjardins, R. L., Dyk, A., Fargione, J. E., Fellows, M., Filewod, B., Hessing-Lewis, M., Jayasundara, S., Keeton, W. S., Kroeger, T., Lark, T. J., Le, E., Leavitt, S. M., LeClerc, M.-E., … Kurz, W. A. (2021). Natural climate solutions for Canada. *Science Advances*, *7*(23), eabd6034. https://doi.org/10.1126/sciadv.abd6034

Government of British Columbia. (2025a). *CleanBC Communities Fund*. Environmental Protection and Sustainability. https://www2.gov.bc.ca/gov/content/environment/climate-change/clean-buildings/cleanbc-communities-fund

Government of British Columbia. (2025b). *Community Forest Agreements*. Timber Harvesting Rights. https://www2.gov.bc.ca/gov/content/industry/forestry/forest-tenures/timber-harvesting-rights/community-forest-agreements

Government of Canada. (2024a, June 5). *Improved forest management on private land (protocol version 1.0)*. Canada.Ca. https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/compendium-protocols/federal-offset-protocol-improved-forest-management-private-land.html

Government of Canada. (2024b, August 7). *Facilitating Projects on Crown and Public Land in Canada's Greenhouse Gas Offset Credit System*. Canada.Ca. https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/indigenous-engagement/facilitating-projects-crown-public-land.html

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*, 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

Kumar, L., & Mutanga, O. (2017). Remote Sensing of Above-Ground Biomass. *Remote Sensing*, *9*(9), 935. https://doi.org/10.3390/rs9090935

Lamb, R. L., Hurtt, G. C., Boudreau, T. J., Campbell, E., Sepúlveda Carlo, E. A., Chu, H.-H., De Mooy, J., Dubayah, R. O., Gonsalves, D., Guy, M., Hultman, N. E., Lehman, S., Leon, B., Lister, A. J., Lynch, C., Ma, L., Martin, C., Robbins, N., Rudee, A., … Tang, H. (2021). Context and future directions for integrating forest carbon into sub-national climate mitigation planning in the RGGI region of the U.S. *Environmental Research Letters*, *16*(6), 063001. https://doi.org/10.1088/1748-9326/abe6c2

Liu, N., Harper, R., Handcock, R., Evans, B., Sochacki, S., Dell, B., Walden, L., & Liu, S. (2017). Seasonal Timing for Estimating Carbon Mitigation in Revegetation of Abandoned Agricultural Land with High Spatial Resolution Remote Sensing. *Remote Sensing*, *9*(6), 545. https://doi.org/10.3390/rs9060545

Metsaranta, J. M., Hudson, B., Smyth, C., Fellows, M., & Kurz, W. A. (2023). Future fire risk and the greenhouse gas mitigation potential of forest rehabilitation in British Columbia, Canada. *Forest Ecology and Management*, *529*, 120729. https://doi.org/10.1016/j.foreco.2022.120729

Meyer, H., Reudenbach, C., Wöllauer, S., & Nauss, T. (2019). Importance of spatial predictor variable selection in machine learning applications – Moving from data reproduction to spatial prediction. *Ecological Modelling*, *411*, 108815. https://doi.org/10.1016/j.ecolmodel.2019.108815

Mina, M., Messier, C., Duveneck, M. J., Fortin, M., & Aquilué, N. (2022). Managing for the unexpected: Building resilient forest landscapes to cope with global change. *Global Change Biology*, *28*(14), 4323–4341. https://doi.org/10.1111/gcb.16197

Ministry of Forests. (2024). *Forest Carbon Initiative—Province of British Columbia*. Www2.Gov.Bc.Ca. https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/natural-resources-climate-change/natural-resources-climate-change-mitigation/forest-carbon-initiative

Ploton, P., Mortier, F., Réjou-Méchain, M., Barbier, N., Picard, N., Rossi, V., Dormann, C., Cornu, G., Viennois, G., Bayol, N., Lyapustin, A., Gourlet-Fleury, S., & Pélissier, R. (2020). Spatial validation reveals poor predictive performance of large-scale ecological mapping models. *Nature Communications*, *11*(1), 4540. https://doi.org/10.1038/s41467-020-18321-y

Schuldt, A., Liu, X., Buscot, F., Bruelheide, H., Erfmeier, A., He, J., Klein, A., Ma, K., Scherer-Lorenzen, M., Schmid, B., Scholten, T., Tang, Z., Trogisch, S., Wirth, C., Wubet, T., & Staab, M. (2023). Carbon–biodiversity relationships in a highly diverse subtropical forest. *Global Change Biology*, *29*(18), 5321–5333. https://doi.org/10.1111/gcb.16697

Sharma, T., Kurz, W. A., Fellows, M., MacDonald, A. L., Richards, J., Chirsholm, C., Seutin, G., Richardson, K., & Keenleyside, K. (2023). *Parks Canada Carbon Atlas Series: Carbon Dynamics in the Forests of National Parks in Canada* [Scientific Report]. Parks Canada Agency. https://publications.gc.ca/collections/collection_2024/pc/R62-581-2023-eng.pdf

Smyth, C., Metsaranta, J., Fortin, M., Le Noble, S., MacDonald, H., Wolfe, J., Boisvenue, C., Laganière, J., Krakowski, J., Zhu, K., Pare, D., Tompalsk, P., Emilson, E. J. S., Webster, K., Dosanjh, M., Venier, L., & Edwards, J. (2023). *2023 Blueprint for Forest Carbon Science in Canada* (Canadian Forest Service, p. 50). Natural Resources Canada. https://ostr-backend-prod.azurewebsites.net/server/api/core/bitstreams/2d5ac1e5-9320-470c-af81-542002cf1e3e/content

Sothe, C., Gonsamo, A., Arabian, J., Kurz, W. A., Finkelstein, S. A., & Snider, J. (2022). Large Soil Carbon Storage in Terrestrial Ecosystems of Canada. *Global Biogeochemical Cycles*, *36*(2), e2021GB007213. https://doi.org/10.1029/2021GB007213

Thompson-Nicola Regional District. (2025). *Regional growth strategy bylaws*. https://www.tnrd.ca/regional-government/bylaws/

Walker, W. S., Gorelik, S. R., Cook-Patton, S. C., Baccini, A., Farina, M. K., Solvik, K. K., Ellis, P. W., Sanderman, J., Houghton, R. A., Leavitt, S. M., Schwalm, C. R., & Griscom, B. W. (2022). The global potential for increased storage of carbon on land. *Proceedings of the National Academy of Sciences*, *119*(23), e2111312119. https://doi.org/10.1073/pnas.2111312119

Yang, H., Ciais, P., Frappart, F., Li, X., Brandt, M., Fensholt, R., Fan, L., Saatchi, S., Besnard, S., Deng, Z., Bowring, S., & Wigneron, J.-P. (2023). Global increase in biomass carbon stock dominated by growth of northern young forests over past decade. *Nature Geoscience*, *16*(10), 886–892. https://doi.org/10.1038/s41561-023-01274-4

APPENDIX A. Stakeholders' interview guide

Perceptions of Carbon Sequestration and Forest Conservation in the Clearwater Valley (buffer area for Wells Gray Provincial Park)

1. Introduction

1.1. Thesis background

I aim to assess the ecological, economic, and social value of carbon sequestration in the private lands of the buffer area of Wells Gray Provincial Park in the Clearwater Valley, as well as the current economic conditions and potential future benefits of these territories as part of carbon offset projects. This area is critical due to its ecological importance as a biodiversity hotspot of interior BC. However, it has undergone different management processes, gradually losing its ecological importance and the possibility of stabilizing or increasing its carbon sequestration potential.

1.2. Purpose of the Interview

That is why, as part of the social dimension, I aim to gain insights from people with different connections (scientific expertise, land knowledge and management, decision-making) with the territory about its forest's carbon sequestration potential.

1.3. Consent

This conversation will be recorded by Microsoft Teams if virtual or by a recorder if in-person, and will be transcribed through the TurboScribe Premium software to identify the key themes discussed. Once the transcript is completed, it will be sent via email for your review, edit and approval. Please let me know if you prefer to have complete anonymity or be identified through pseudonyms or codes in the documents produced from this research.

2. Interview

2.1. Agreement with Forest Conservation

Ecosystem Services and Climate Role:

- ○ What are your thoughts on the effectiveness of the forests to mitigate climate change through carbon sequestration?

Knowledge of Local Conservation Efforts:

- ○ Are you aware of any initiatives in this region linked to forest conservation on private lands?
- ○ Do you believe that the conservation of forests in private lands could impact ecological processes in the provincial park?
- ○ Do you think forest conservation or restoration is viable for the area's landowners?

Perceived Barriers:

- ○ How do you think land-use decisions in the buffer areas could prioritize the benefits of carbon sequestration?
- ○ What are the biggest challenges to forest conservation in this area?
- ○ Do you believe there is enough local or provincial support to conserve forests here? Government?

2.2. Economic and Social Value of Carbon Sequestration

- ○ How do you think forest conservation impacts the local economy and employment opportunities?
- ○ How important do you think forest conservation is for tourism and recreation in the Clearwater Valley?

2.3. Carbon offset projects for forest conservation

Forest conservation and management practices have the potential to provide economic co-benefits, such as carbon credits. These credits can be sold in the voluntary carbon market, so the companies that cannot reach their greenhouse gas emission targets can purchase carbon offset credits by investing in environmental projects. Those projects can range in scale from very small (e.g., reducing a few hundred tonnes of CO2 per year) to very large (e.g., millions of tonnes reduced per year).

Carbon Credit Programs:

- Would implementing a forest conservation project to sell carbon credits be viable in the area?
- Do you think this type of project could benefit the community apart from the land owner or the organization?
- Do you think the local community or the municipal government can support this project?

Incentives for Landowners:

- Alternatively, do you know any regional programs that pay landowners to maintain forests for carbon sequestration? Would you support such initiatives?

APPENDIX B. Summary of field training data processing for model training

Forest structure

The 3 acres (0.08 km^2) of protected forest tree inventory between the Edgewood Blue and the Land Conservancy properties encompassed 1,247 trees of eight species. The three most common and dominant leaf species are: white spruce (50%), subalpine fir (18.6%), and trembling aspen (8.1%).

Table AB1 lists the species with their importance values. Importance values are calculated as the sum of the percent population and the percent leaf area. High importance values do not necessarily mean that these trees should be encouraged in the future for vegetation management; instead, these species currently dominate the forest structure.

Species name	**Percent population**	**Percent Leaf Area**	**Importance value**
White spruce (*Picea glauca*)	50.0	39.6	89.6
Subalpine fir (*Abies lasiocarpa*)	18.6	15.7	34.3
Trembling aspen (*Populus tremuloides*)	8.1	16.2	24.3
White birch (*Betula papyrifera*)	7.3	12.1	19.4
Western hemlock (*Tsuga heterophylla*)	5.6	1.7	7.3
Lodgepole pine (*Pinus contorta*)	2.3	0.6	2.9
Black cottonwood (*Populus balsamifera*)	1.4	6.1	7.4
Western red cedar (*Thuja plicata*)	1.3	5.2	6.5

Table AB1 Tree species abundance distribution in the 3-acre forest plot

Evergreen coniferous forest dominates the study area's vegetative cover in abundance and the leaf area, but there is also a presence of mixed deciduous tree species. This forest composition corresponds to most low to medium-elevation forests of the Central Interior Ecoprovince. White spruce and subalpine fir join lodgepole pine as the dominant conifers over much of the moister southern half of the Interior Plateau (Klinkenberg, 2023). Nevertheless, old-growth forests in the region are dominated by western hemlock and western redcedar, while vegetation is relatively diverse, and deciduous forests are increasing towards the northeast (Demarchi, 2011).

Regarding the deciduous tree species, the occurrence of stands of trembling aspen and paper birch indicates finer soil materials (Demarchi, 2011), while black cottonwood is characteristic of past fluvial processes, since it regenerates well after floods, channel migration, or other disturbances that expose bare mineral soil (Hood & Naiman, 2000). Given the abundance and diversity of the tree species, it is crucial to determine the forest's successional stage through a complementary analysis of the DBH distribution, as shown in Figure AB1.

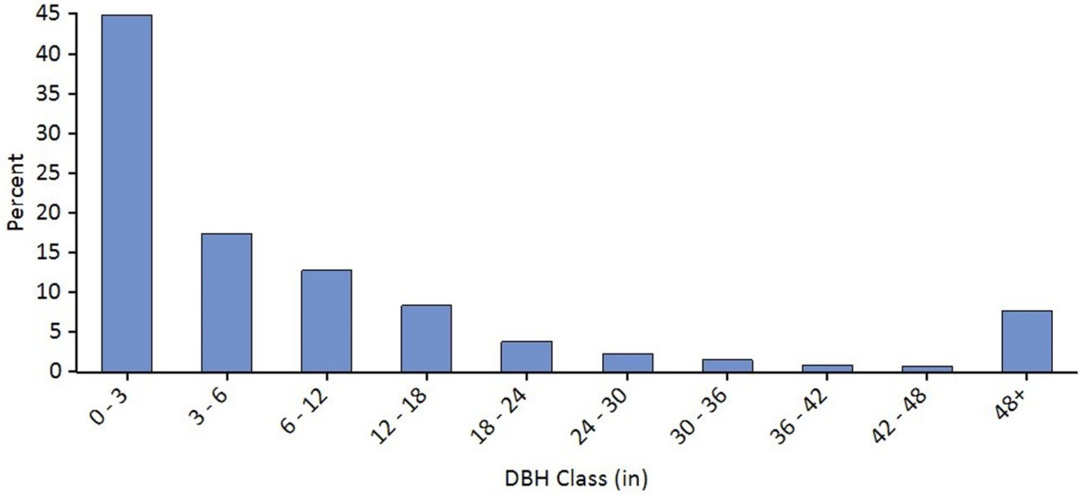


Figure AB1 DBH distribution of the trees sampled in the western protected forest plots

The DBH distribution of the western forest sample shows that about 45% of the trees fall within the smallest diameter class (0–3 inches), followed by a steadily declining proportion across larger classes and only a few trees in the mid-range. Notably, there is a slight increase in the largest DBH class (> 48 inches). These height distributions provide evidence for the development of a continuous canopy from the ground to the tops of the tallest trees with Douglas-fir occupying the highest canopy positions and western hemlock and western redcedar filling in the intermediate canopy positions in the Pacific Northwest forest of North America (Freund et al., 2015).

Carbon storage and sequestration estimation

In the Upper Clearwater Valley, private landowners manage a mosaic of land uses, including residential development, small-scale agriculture, grazing, and forested areas. Given that most properties span approximately 10 acres, it is reasonable to assume that 2 to 5 acres could be allocated for forest conservation, particularly since many landowners already maintain forest patches. This integrated land-use approach offers a promising pathway for advancing forest conservation across the valley by emphasizing the ecological and economic value of these forests without disrupting existing land-based livelihoods.

Total carbon storage refers to the carbon currently locked in above ground and below grand biomass of live trees. In contrast, carbon sequestration measures the additional carbon that forests absorb yearly through growth. Carbon storage and sequestration are typically expressed in terms of CO_2 equivalent (CO_2eq). Table AB2 presents the carbon storage amount and CO_2eq of the trees sampled in the 3-acre protected forest for each species.

Species name	**Carbon storage (ton)**	**Carbon storage (%)**	**CO_2 eq (ton)**
White spruce (*P. glauca*)	446.3	47.5	1,636.5
Trembling aspen (*P. tremuloides*)	186.2	19.8	682.7
White birch (*B. papyrifera*)	106.0	11.3	388.5

Species name	**Carbon storage (ton)**	**Carbon storage (%)**	**CO_2 eq (ton)**
Western red cedar (*T. plicata*)	50.7	5.4	186.0
Subalpine fir (*A. lasiocarpa*)	53.0	5.6	194.3
Black cottonwood (*P. balsamifera*)	28.4	3.0	104.3
Western hemlock (*T. heterophylla*)	13.1	1.4	48.2
Lodgepole pine (*P. contorta*)	0.9	0.1	3.4
Total	939.4	100	3,444.9

Table AB2 Carbon storage of the trees in the western protected forest plots

The carbon storage data reinforce the DBH-based interpretation of this forest as a structurally complex system dominated by late-successional species. White spruce alone accounts for nearly half of the total carbon (47.5%), indicating the presence of large, long-lived individuals that align with the largest DBH classes. Trembling aspen (19.8%) and paper birch (11.3%) are major contributors, with spruce comprising 78% of the total carbon stock. This dominance of large conifers and mature hardwoods is consistent with developing a replaced canopy posterior to the wildfire disturbance (Demarchi, 2011).

The next step is to estimate the forest's carbon storage and carbon sequestration capacity to evaluate its capacity for mitigating climate change effects through carbon sequestration. For this analysis, Figures AB3 and AB4demonstrate the carbon stock and annual carbon sequestration value per species in the 3-acre pilot study area.

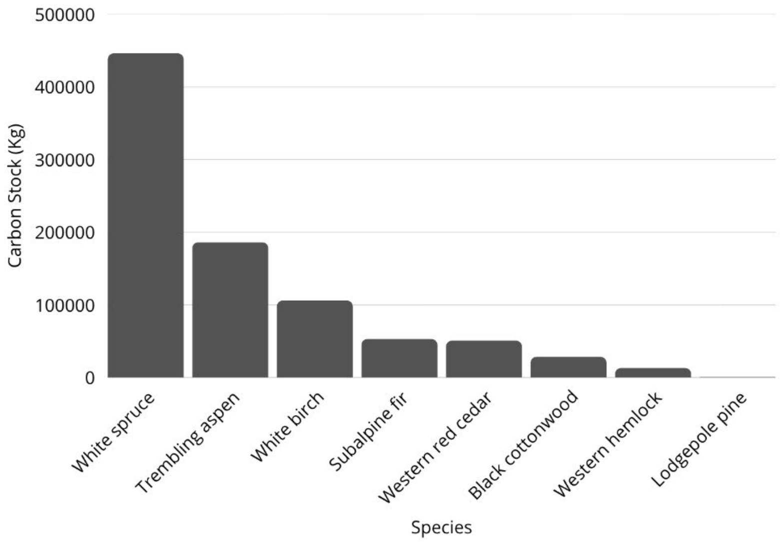


Figure AB3 Carbon stock of the 3-acre forest calculated by i-Tree Eco Tool (2024)

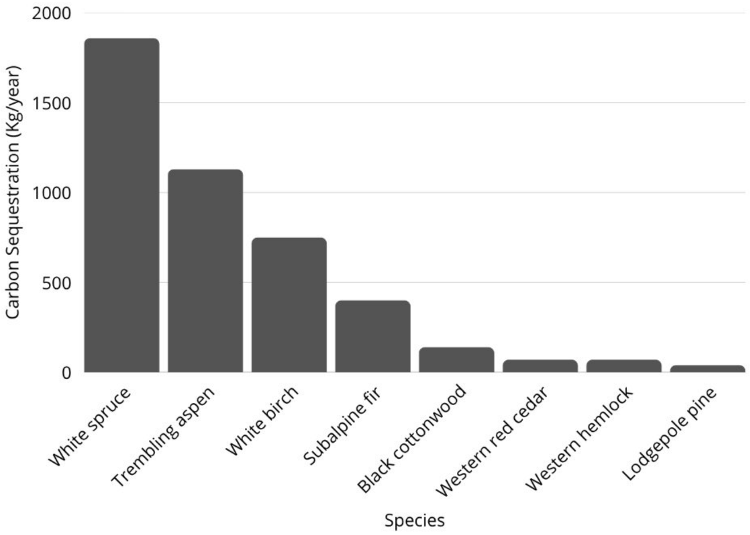


Figure AB4 Annual gross carbon sequestration of the 3-acre forest calculated by i-Tree Eco Tool (2024)

Of the species sampled, white spruce stores and sequesters the most carbon (approximately 47.5% of the total carbon stored and 39.4% of all sequestered carbon). The gross sequestration of the 3-acre study area trees is about 4,730 kg/yr. The amount of carbon annually sequestered increases with the size and health of the trees. This highlights the forest's role in offsetting emissions and strengthens the case for long-term protection and management in the valley. To contextualize the relative value of carbon storage in terms of community benefits, the 2-acre area of carbon storage equals the annual carbon emissions from 665 automobiles or 272 single-family houses (Nowak & US Forest Service, 2021).

APPENDIX C. Confusion matrix and variables of importance from the Random Forest tree species classification model

Western side

Variable	Importance score
DBH	70.43095
zq90	34.27995
zq75	31.79400
zq80	30.19661
zq85	23.12538

Table AC1. Score of the top 5 most important variables of the species classification model in the western area of the study site

Eastern area

Variable	Importance score
DBH	48.34969
zmax	26.83918
East_chnl_base	26.78321
za95	26.59407
East_openness_pos	23.75375
East_valley_depth	23.03070

Table AC2. Score of the top 5 most important variables of the species classification model on the eastern area of the study site