MITIGATING FORESTED WATER SUPPLY CARBON LOADING THROUGH TIMBER HARVESTING

by

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Abstract

Access to clean drinking water is a human right and forested surface reservoirs provide many of the world's most sustainable, easily treatable water supplies. Continued benefits from these sources requires proactive environmental management. Concentrations of dissolved organic carbon (DOC), a naturally occurring water constituent, are rising in many regions for a variety of reasons. This is increasing water treatment difficulty and cost, including in Nova Scotia's Pockwock watershed, from which over 200,000 people in Halifax Regional Municipality receive water. Watershed managers seek a proactive approach to mitigate future increases and reduce lake DOC concentrations.

Through this study, I aim to understand the role of forest management and climate change in landscape carbon dynamics and export. Chapter 1 provides an overview of the research and methods employed. Chapter 2 uses field data collected from the Pockwock watershed to calibrate the application of regional forest growth models in carbon modelling. Chapter 3 uses the calibrated growth models with a bespoke forest management model and a custom implementation of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to simulate carbon outcomes of varying management scenarios. Chapter 4 ties the outcomes of this simulation modelling to hydrologic export using calibrated catchment models and DOC concentration observations to predict future DOC export under different management and climate scenarios.

Results indicate that timber harvesting reduces carbon in dead organic matter pools and DOC exports. Severity of future climate scenario change tends to correlate positively with DOC export increases, but this relationship is not as strong as timber harvesting and comes with some key uncertainties. DOC export reductions from timber harvesting may contribute to future water treatability over baseline, non-harvest scenarios. Forest management must balance producing easily treatable water with other ecosystem services and environmental values, and this may require challenging traditional notions of the right way to manage a source water supply. Examining the DOC export outcomes due to forest management and climate change scenarios is a novel contribution to the field and an important step in understanding the consequences of anthropogenic activities on critical water supplies.

List of Abbreviations Used

Abbreviation	Meaning
AG	Aboveground
BA	Basal area
BG	Belowground
C	Carbon
CBM-CFS3	Carbon budget model of the Canadian forest sector (v3)
CC	Clear cut (harvest type)
CLFM	Crown lands forest model
CLFMLC	Crown lands forest model landbase classification
DBH	Diameter at breast height (1.3 m from ground)
DOC	Dissolved organic carbon
DOM	Dead organic matter
FEC	Forest ecosystem classification
G&Y	Growth and yield (models)
GCM	Global climate model
GRG	Generalized reduced gradient
HRM	Halifax Regional Municipality
LC	Land capability
LiDAR	Light Detection and Ranging
MADR	Mean annual disturbance rate
MAI	Mean annual increment
MAT	Mean annual temperature
MDR	Managed disturbance regime
MV	Merchantable volume
NDR	Natural disturbance regime
NDSLF	Nova Scotia Department of Lands and Forestry (now NSDNRR)
NEP	Net ecosystem productivity
NOM	Natural organic matter
NS	Nova Scotia
ns	Not significant (statistically)
NSDNR	Nova Scotia Department of Natural Resources (now NSDNRR)
NSDNRR	Nova Scotia Department of Natural Resources and Renewables
NSE	Nash-Sutcliffe efficiency (score)
NSERC	Natural Sciences and Engineering Research Council
PET	Potential evapotranspiration
SBW	Spruce budworm (*Choristoneura fumiferana* Clem.)
SOC	Soil organic carbon
SSP	Shared socioeconomic pathway
TOC	Total organic carbon

Unit Abbreviations

Symbol	Name
cm	Centimetres
g	Gram
Gg	Gigagrams (10^9 g)
ha	Hectares
kg	Kilogram (10^3 g)
L	Litre
m	Metres
Mg	Megagram(s) (10^6 g)
mg	Milligram (10^{-3} g)
Pg	Petagram(s) (10^{15} g)
yr	Year

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1 Introduction

Forests provide high-quality water and are relied upon globally for drinking-water supplies that are naturally filtered and easily treatable (Ernst *et al*. 2004). Ensuring that forests continue to provide water of suitable quality often falls to managers within a water utility who must either manage lands directly or work with a variety of other landowners to ensure that management best supports water treatability. While this has traditionally meant limiting and containing the effects of human influence on water supplies, indirect effects of human activities now require our attention, and what we are learning may require reshaping how we view forest management in a source-water supply.

1.1 Background & Rationale

Throughout a forest's lifecycle, dead organic material is shed to the ground, whether through annual leaf litter, when trees succumb to mortality (naturally or otherwise), or as any other dead biomass comes to rest on the forest floor or in forest soils. This, however, is hardly the final resting place for the carbon (C) contained in the biomass. As microbes break down the dead organic matter (DOM), a portion of DOM will become recalcitrant and resistant to further decomposition or loss from the system (Prescott 2010). Another portion will become labile C with a relatively short expected residence time and is susceptible to loss through respiration, the dominant export pathway, or other means (Parton *et al*. 1987). Water in contact with all layers of the forest floor and the mineral soils below can also mobilize labile C, carrying it along hydrologic paths, ultimately to streams, lakes, and possibly to the ocean (McDowell and Wood 1984; Wu *et al*. 2014). Mobilized C is a component of natural organic matter (NOM) and is quantified as total organic carbon (TOC). The smallest carboniferous molecules, able to pass through a 0.45 μm membrane, are classified as dissolved organic carbon (DOC) (Filella 2009). Naturally produced, DOC performs several important roles in aquatic environments (Schindler 1971) and represents a key mass transfer process between terrestrial and aquatic systems (Hope *et al*. 1994). Nakhavali *et al*. (2021) estimated that approximately 15% of global net ecosystem productivity is leached as DOC, a total of 240 teragrams (Tg) of C annually according to Li *et al*. (2017). As with many environmental systems, terrestrial-aquatic C transfers are naturally highly dynamic and subject to change due to human influences.

Over the past 20-30 years, researchers have noted an upwards trend in worldwide surface water DOC concentrations (Couture *et al*. 2012), initiating studies to understand why. Elevated DOC concentrations were observed where acidic sulphate deposition was substantially reduced, and researchers suggested a causal relationship between the two (Skjelkvåle *et al*. 2005; Monteith *et al*. 2007). Emissions reductions aimed at mitigating acidic deposition were linked to increased environmental and stream water pH in formerly highly affected areas (Stoddard *et al*. 1999). Other studies found that warming temperatures associated with climate change were responsible for increased DOC in streams (Freeman *et al*. 2001). More recent research has uncovered a strong inverse relationship between ionic strength and DOC, suggesting that soil Ca^{2+} depletion may be a driver of continued DOC mobilization into the future (Lawrence and Roy 2021). It is likely that increasing DOC is caused by a combination of changes in acid deposition regime, corresponding changes in soil chemistry (both new and historical), temperature, and precipitation patterns as a result of climate change, where the relative importance of either factor is regionally dependent (Winterdahl *et al*. 2016). Some researchers have suggested that increases in DOC represent a return to pre-industrial conditions, and consequently may hit a natural ceiling (Monteith *et al*. 2007; Evans *et al*. 2012; Meyer-Jacob *et al*. 2019). However, surface-water DOC increases in areas with historically low acidic deposition are exceeding pre-industrial levels (de Wit *et al*. 2021). Both acidifying deposition reductions and climate-related variables are indirect ways that anthropogenic activities influence C export, but human interventions can more directly affect DOC.

Environmental management efforts that affect either DOM accumulation, forest soils, or the microclimate of a forest can impact DOC production and export. Timber harvests typically cause short-term DOM increases by leaving branches and tree-tops on the forest floor, and tree roots in the ground (Morris 2009; Webster *et al*. 2022). Much of the labile C that originates through decay from this DOM will be lost rapidly either to the atmosphere or hydrologic export. A number of microclimate variables that influence decay rate and C export may be affected by canopy removal, especially soil temperature and moisture and the quantity and timing of water fluxes through the soil (Sørensen *et al*. 2009; Wu *et al*. 2014; Webster *et al*. 2022). In the long term, timber harvesting diminishes the accumulation of DOM in slower-decaying soil pools and has been found to contribute to lasting reductions in DOC export (Yamashita *et al*. 2011; Cawley *et al*. 2014; Smiley and Trofymow 2017; Lajtha and Jones 2018). Together, these direct and indirect effects demonstrate the potential to influence DOC production through forest management, both in the short and long term. These forest management efforts could increase or decrease C export.

Studies about the effects of management on forest C storage often proceed with a presumption that sequestration should be maximized as a contribution to climate-change mitigation (Cooper 1983; Lal 2005; Mäkipää *et al*. 2023). Researchers examining the effects of forest management on DOC are more likely to take a neutral stance, studying the outcomes with no stated favour towards reductions or increases. While some studies from agriculture (Graeber *et al*. 2012; Stanley *et al*. 2012) and wetland restoration (Koskinen *et al*. 2017) have attempted to address concerns about acute DOC loading, most forest research is currently attempting simply to better understand the processes that affect export one way or another. A question that has not yet been adequately addressed in the literature is whether it is possible to manage forests to minimize DOC export. Understanding that there is a positive correlation between DOM pool volume and labile C production (Park and Matzner 2003; Harmon *et al*. 2011), and given the seeming consensus that increased C sequestration is a laudable goal, the pursuit of anything else seems unlikely. However, with surface water DOC concentrations rising globally and climate change a likely driver of at least part of this shift, managing for this goal may eventually become necessary. Under a management regime with very specific objectives, answering this question may in fact be urgent.

Water treatment for human consumption requires removal of a variety of constituents. Natural organic matter includes both DOC and particulate organic carbon (POC), differentiated by their particle size and ability to pass through a 0.45 μm filter (Szymczycha *et al*. 2017). DOC, particularly difficult to remove from solution, is typically removed during water treatment through the process of flocculation – adding a coagulant to water and agitating to facilitate formation of larger particles that can be filtered out (Matilainen *et al*. 2010). More DOC requires more coagulant which costs both more money for acquiring and storing the chemical, and more time to allow for flocculation and filter downtime for cleaning. Flocculant acquisition and use accounted for 12.9% of total energy consumption at one studied water supply plant (Santana *et al*. 2014), expenditures that will also increase with higher DOC concentrations. Additionally, interactions between DOC and chemicals used in the treatment process contribute to disinfection byproduct formation, requiring further treatment for removal and increasing costs (Singer 1999). Historical and continuing DOC increases, the propensity of natural disturbances to increase DOC (Emelko *et al*. 2011), uncertainty about the degree of effect from climate change, and costs associated with treatment led to the formation of a Canadian national network of researchers, water utilities, government agencies, and other partners to address the risk of DOC to drinking water supplies (forWater Network 2024a). These partners have worked together since 2018 to address one unifying question: how do we manage forested drinking water supplies to mitigate risks to water treatability? Researchers are looking closely at the impact of DOC on treatment systems and the factors that contribute to its formation and characteristics in research nodes from coast to coast, including in Atlantic Canada where a team from Dalhousie University examined Halifax Regional Municipality's (HRM) largest water supply, the Pockwock watershed (forWater Network 2024b).

1.1.1 The Pockwock Watershed

Located approximately 20 km northwest of the urban core of HRM, the Pockwock watershed has long been a source of natural resources for the region's inhabitants. The lands in and around the Pockwock watershed were occupied by the Indigenous Mi'kmaq, who resided in, hunted, and gathered resources from this area, especially during winter when groups moved away from the coast (Hammonds Plains Historical Society 2018). Grants issued to European settlers in the late 18th century for Hammonds Plains and the adjacent Pockwock watershed started timber harvesting and trading to capitalize on the abundant forest in this area. To service this burgeoning timber trade, several mills were built on the shores of Pockwock Lake and its outflows, milling timber including from the privately owned woods of the Pockwock watershed, a legacy that lasted until the 1970's (Hammonds Plains Historical Society 2018). The watershed was then identified as the City of Halifax's next water supply, and the privately owned and managed forest land was appropriated by the Province. The region's water utility, Halifax Water, guides watershed management with the objective of protecting water quality and treatability, including through forest management interventions such as timber harvesting (Halifax Water 2009).

The 5,400 ha Pockwock watershed includes 4,200 ha of primarily forested land that drains to Pockwock Lake. The remainder of the watershed is comprised of open water (1,080 ha) including Pockwock Lake, and various human uses (120 ha) including utility and transportation corridor and developments on the NE side of a major highway. From this lake, Halifax Water draws an average of 91,583 m^3 of water daily for treatment and distribution to over 200,000 people in multiple communities (Halifax Water 2023). Water is treated in the J.D. Kline water supply plant (JDKWSP), which was constructed in 1977 and uses a dual-media direct-filtration process, including flocculation with aluminum sulphate to remove DOC along with treating other water quality parameters (Halifax Water 2023). Water samples collected at the JDKWSP show similar results to Langelaan (2022) that TOC is almost entirely comprised of DOC (Halifax Water, unpublished dataset), therefore the two will be used interchangeably in this research. Due in part to a 123% increase in lake-water total organic carbon (TOC) between 1977 and 2019, upgrades are needed to the JDKWSP to facilitate additional pre-treatment (Halifax Water 2020, p. 27) that will cost in excess of $130 million (CBCL Limited 2022). Previous study of the Pockwock watershed found that TOC in its source waters is > 90% comprised of DOC, with variability between the watershed's subcatchments (Langelaan 2022). Additionally, water samples routinely collected by the region's water utility show that DOC represents the vast majority of C in lake water drawn for treatment (Halifax Water, unpublished dataset). Watershed managers are seeking to understand whether proactive forest timber management can at the very least slow increases in forest C exported to the lake, to prevent the need for further upgrades in the future.

1.2 Purpose

The purpose of this research is to determine whether forest timber management can mitigate future DOC loading in Pockwock Lake and other similar source water systems. Understanding the relationship between forestry interventions and DOC export will allow for specific management recommendations that support the watershed providing a high quality, easily treatable, and sustainable water supply into the future. To tackle this overarching question, I will address three individual research questions (RQ):

- **RQ1**: What is the DOC export regime in the Pockwock watershed?
- **RQ2**: What are the short- and long-term effects of timber harvesting on DOC export?
- **RQ3**: What are the long-term effects of climate change on DOC export?

Each of these questions addresses the need for an understanding of DOC dynamics in the Pockwock watershed, and answering them supports the objective of producing management recommendations to Halifax Water. Answering RQ1 will establish the relationship between the quantity of DOC exported from each of the watershed's subcatchments and natural, geographic, and climate variables. I can then address RQ2 by observing the effects of planned and monitored forest interventions to determine how DOC export responds in the short term (<3 years) and then use these results to inform simulation modelling that predicts long-term effects. Integrating future climate scenarios into simulation modelling will provide insights into the potential impacts of changing temperature and precipitation regimes on both labile C production and DOC export, answering RQ3. To address these three questions, my research is guided by the following three research objectives (RO):

- **RO1**: Characterize the production and export of DOC in the Pockwock watershed.
- **RO2**: Determine the short-term effects of timber harvesting on DOC export through empirical measurements, then predict long-term effects using an integrated modelling framework.
- **RO3**: Assess the long-term effects of climate change on DOC export through use of climate scenarios in the integrated modelling framework.

Based on my understanding of the literature and environmental conditions in the Pockwock watershed, I developed the following three hypotheses about the outcomes of this research:

- Hypothesis 1: Timber harvests, as practiced in the Pockwock watershed, will not cause any immediately appreciable changes in DOC, but by reducing DOM accumulation over the long term, we project an inverse relationship between timber harvest intensity and DOC exports.
- Hypothesis 2: More-severe climate scenarios will correlate with higher DOC export predictions from modelling.
- Hypothesis 3: Timber-harvesting-induced DOM reductions and corresponding DOC export decreases will mitigate some, but not all, DOC export increases caused by changing temperature and precipitation regime of climate change scenarios.

Hypotheses 1 and 2 are well supported in the literature and finding support for them in the Pockwock watershed would be further evidence of these established relationships between timber harvesting, climate change, and DOC export regimes. Hypothesis 3 reflects the substantial changes that can occur in decay and C export because of changing climate, against the long lag times and slight long-term DOC export reductions that the literature indicates are associated with timber harvests. Testing these hypotheses will require extensive characterization of the study area and simulation modelling capable of testing the effects of timber harvest under a changing climate, including the effects of temperature and more-erratic precipitation regimes.

1.3 Research Approach

Predicting future DOC export under different forest management and climate scenarios was accomplished in two steps: field measurements and simulation modelling. Understanding the forest and current DOC export regime (RQ1) necessitated fieldwork to measure forest characteristics and both the hydrologic properties of the watershed and year-round DOC concentrations. Fieldwork was needed to characterize timber harvests and DOC concentrations both during and after harvests, to determine if there is a discernible response to interventions in stream water (RQ2). These relationships were used to calibrate models that helped predict the long-term consequences of timber harvesting on DOC (RQ2) and integrate climate scenarios to elucidate the potential impacts of changing temperature and precipitation regimes (RQ3). The fieldwork necessary for this work is described in subsequent chapters, while the domains of modelling necessary and selection of appropriate models are discussed here.

1.3.1 Modelling

Determining future DOC export regimes under different management and climate scenarios requires three distinct domains of modelling pertaining to C capture, transformation, and export:

- Forest dynamics: natural growth, mortality, and anthropogenic influences
- Biogeochemical processes: how the C in DOM is transformed, transported within the forest, and lost through respiration
- Hydrology: lateral pathway for labile C export

In concert, these three domains simulate forests and the fate of the C that enters them. I briefly explore some of the considerations when selecting models that led to those presented and used in subsequent chapters.

There are many options for each domain, some existing models that accomplish more than one of the required tasks, but no models that accomplish all three. Thus, existing or novel models need to be selected or developed with the explicit intent of interoperability to produce an integrated modelling framework that can accomplish all of the tasks laid out above. Modelling the transformation of C in DOM pools and subsequent loss via respiration and hydrologic export is not novel, and there are existing models or pairings of models to accomplish this task, such as INCA-C (Futter *et al*. 2007). I eschewed such integrated models in favour of single-domain models that require simple inputs and provide outputs that are easily integrated into the next model domain. This led to the development or selection of three separate models to realize the full range of tasks required in this research.

Forest growth and disturbance modelling has long been utilized to help improve the predictability and efficiency of forest management by estimating timber yields (Shifley *et al*. 2017). Newer forest models make use of modern processing power to simulate not only yield but landscape processes such as disturbances, effects on productivity from natural and anthropogenic causes, and other complex variables. For the purposes of this research, I required a model that simulates forest stand growth and biomass accumulation as well as various anthropogenic and natural disturbances. There is a variety of proprietary commercial offerings with a focus on timber supply (e.g. PatchworksTM (Spatial Planning Systems 2009), Woodstock (Walters 1993)), but these were not used due to their cost, focus on future timber supply, and complexity unnecessary to the current task. Landscape models such as LANDIS-II (Scheller *et al*. 2007) have previously been used successfully in this study watershed to determine the effects of climate change on the forest (Steenberg *et al*. 2011; Steenberg *et al*. 2013), and are capable of simulating both natural and anthropogenic disturbances. However, I sought a simpler approach specifically designed to provide the input data required for biogeochemical modelling that came next. For this reason, and also as a learning opportunity, I developed a forest simulation routine that incorporates existing stand data from provincial records and natural disturbance rates from the literature, and stochastically applies both natural and harvest disturbances at prescribed rates. Using yield curves and with further calibration through the results of fieldwork, this model provided the appropriate input data for the next step of modelling, the transformation of C in DOM.

Based on the success of other research (e.g. Smiley and Trofymow 2017), favourable comparison to other similar models (Kim *et al*. 2015), transparency of the model's design (Kurz *et al*. 2009), and flexibility in replicating the model in a novel programming environment, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) was a good fit for this research. The model was replicated in C++ code written within an R programming environment to facilitate ease of interoperability with the designed forest growth and disturbance simulation routine. The compartmentalization of C within different forest floor and soil pools based on relative decay speed paired well with hydrologic modelling, which often considers the different rate of water movement through the forest floor versus mineral soils.

For hydrologic processes, I required a model that could be calibrated using precipitation and flow records obtained from several subcatchments over the study period to predict future flows under different climate regimes. A semi-distributed conceptual model, Hydrologiska Byråns Vattenbalansavdelning (HBV) model (Bergström 1976), can be calibrated using the data available and with minimal additional catchment classification required. Additionally, a recent version of the model, HBV-light (Seibert and Vis 2012), provided a graphic user interface, automatic calibration functions, and batch-run capabilities that make it user friendly. Additionally, HBV-light has been used successfully in several contexts including simulating the impacts of climate change (Horton *et al*. 2022) which demonstrates its good fit for the present research. The data collection and analysis plus modelling steps completed in fulfilment of this research are summarized in a single flowchart that demonstrates data dependencies and the sequence of data processing (Figure 1.1).

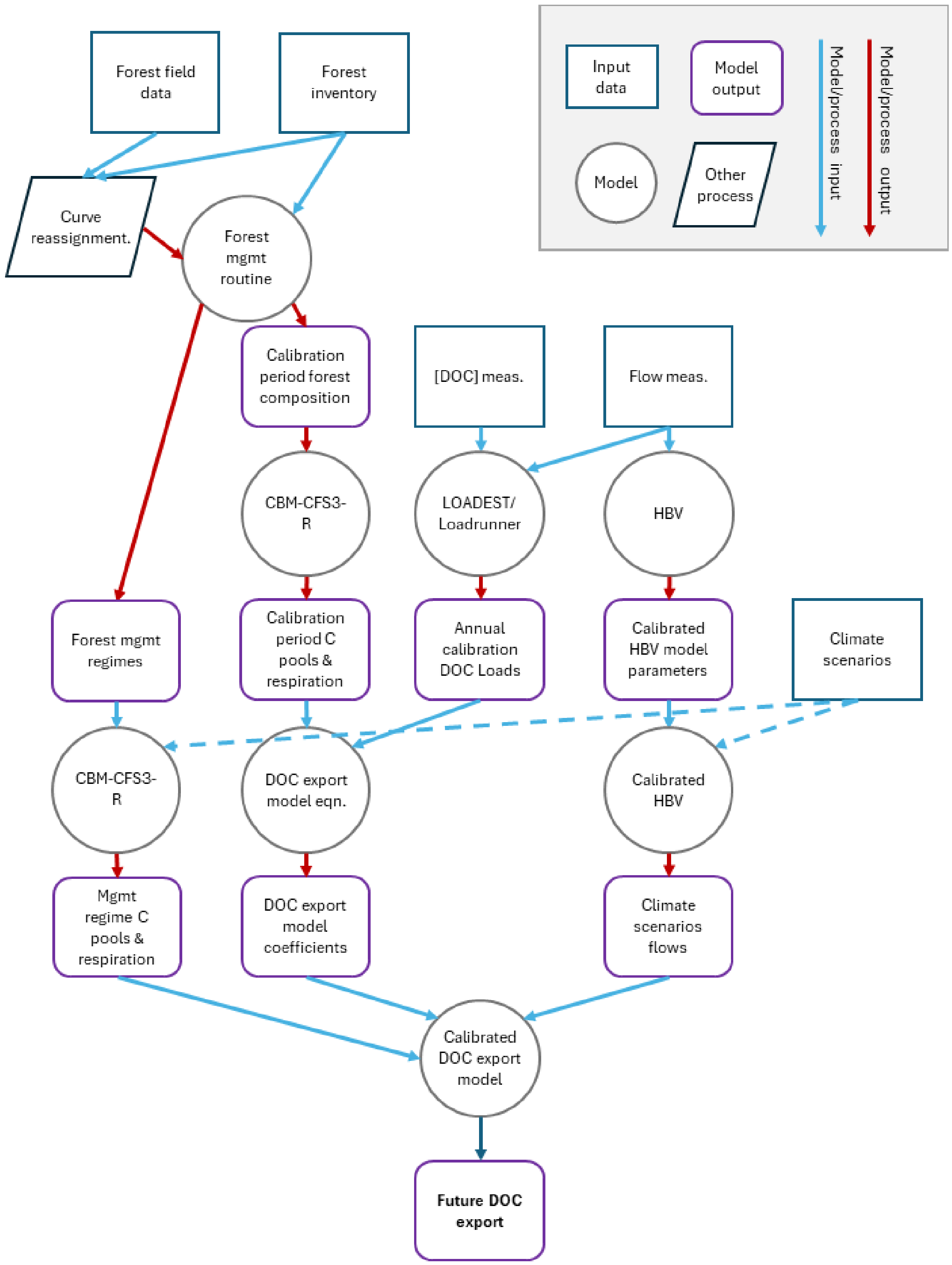

Figure 1.1 Summary of data analysis and modelling conducted for this study including input data (blue boxes), models used (grey circles), other data analysis (black parallelogram), and model data outputs (purple rounded rectangles). The methods section provides further explanation of each step, including abbreviations for models and data.

1.4 Thesis Structure

This thesis is composed of five chapters: an introduction, three manuscript chapters, and a conclusion and discussion chapter. The three manuscript chapters were written for submission to academic journals and serve singular objectives of their own, while supporting the overall purpose of this research.

- Chapter 1 provides an overview of the rationale for the research, a summary of the overall research approach, and research design.
- Chapter 2, “Modelling mesoscale forests”, addresses the question of whether provincial growth and yield curves can be used as the empirical foundation for a novel forest growth routine. Within this chapter, I specifically address whether observations of the watershed’s living biomass, collected through two summers of fieldwork, match expectations from the provincial records.
- Chapter 3, “Where does carbon go?”, uses a novel forest management routine paired with CBM-CFS3 to determine how management affects accumulation and loss of C within the study area. The results of this paper, published in the Journal of Environmental Management, were used to provide labile C pools for hydrologic export in subsequent work.
- Chapter 4, “Timber management reduced DOC export”, uses hydrologic modelling to draw down the supply of labile C from the previous chapter, simulating DOC export. This chapter describes the use of HBV-light and other calculations to estimate flows, annual C loading based on discrete measurements, and the application of climate models to simulate changes in both labile C production and potential export hydrologically. This chapter also provides preliminary results for all three research questions with further discussion in the following chapter, thus representing the confluence of the preceding research efforts.
- Chapter 5 provides higher-level discussion of the results and overall conclusions, highlighting the results’ implications for watershed managers, contributions to the literature, and important avenues for future research.

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2 Modelling Mesoscale Forests

The contents of this chapter were submitted on 28 June 2024 to The Forestry Chronicle and are currently under review for publication. If published within this journal, permission to publish the contents herein within this thesis are retained by the author per the Canadian Institute of Forestry's *Author's Rights* policy. This includes authors' retained right to "[r]e-use all or part of their article(s) in subsequent publications provided the source is acknowledged and no financial gain is realized."

Abstract

Forest models can be developed from empirical relationships between stand attributes, including age, and yield. Though forest modelling has proliferated to include diverse models capable of predicting growth responses to environmental changes, empirical growth and yield (G&Y) models remain popular with forest managers for their simplicity and utility. It is important to apply models at the spatial levels at which they were developed to avoid the fallacy of disaggregation. This study attempted to determine whether regionally aggregated G&Y curves perform adequately when applied at the sub-regional scale, and if not, if their application can be modified to better model a mesoscale forest. We studied a mesoscale forested watershed in Nova Scotia, Canada, to determine if a regional G&Y model could predict stand merchantable volume (MV) using only data available from a photogrammetric provincial forest inventory. Initial results demonstrated that yield curves significantly underestimated stand MV compared to 700 forest cruise point observations throughout the study area. Yield curves were reassigned based on observations and discussion with local managers, and subsequently generated estimates of stand MV not significantly different from observations. We found that while regional growth models are not ideal for application at the mesoscale, when properly calibrated through field observations, can offer insights into the current conditions and future potential of a forest with minimal additional data collection required.

2.1 Introduction

Forest managers have attempted to predict forest growth through models for centuries. This has evolved from 18th and 19th century yield tables (e.g., Paulsen 1795; Cotta 1821; both cited in Porté and Bartelink 2002), through more advanced statistical, variable-density yield equations (MacKinney and Chaiken 1937), to hybrid process-empirical models designed to predict effects of changing environmental variables on forest growth (Landsberg 2003). The intent with these models is to make predictions, but the process and data required varies based on the outputs of interest and how the results will be used. In this study, we examined empirical, regional forest growth and yield (G&Y) models and evaluated the accuracy of their application at scales different from that which they were derived. Our goal was ultimately to accurately apply regional growth models to a sub-regional forest for subsequent use in forest carbon research.

Forest models are traditionally classified as either empirical or process-based (mechanistic), while a newer class of models combines aspects of both, referred to as hybrid models. Practically, empirical models are used when the main goal is prediction, especially of merchantable volume (MV) in fixed geographic regions, while process models are more frequently used to gain an understanding of system dynamics (Burkhart and Tomé 2012), including the effects of environmental changes (Korzukhin *et al*. 1996). Despite the power of process models to make predictions in dynamic systems, the overall simplicity and utility commonly characteristic of empirical models ensures their continued popularity among researchers and practitioners.

Many empirical models have simpler data requirements than process or hybrid models, more easily obtained using techniques familiar to foresters and making them ideal for forest managers. Vanclay (1994) states that growth models must ultimately be viewed as tools to help better manage forests and should be used in a “hands-on way” by the managers themselves. Simpler and familiar data requirements, especially in combination with more recent innovations in the models themselves, drive continued and even increased utility to managers (Korzukhin *et al*. 1996; Shifley *et al*. 2017) that ensures empirical growth models remain an important tool in forest management. An increased focus on carbon capture in forests has also lent itself well to empirical models (Kurz *et al*. 2002). A proven ability to forecast MV combined with well-studied relationships between bole, branch, and root volumes, and the carbon contents thereof, make empirical models a practical tool for predicting carbon accumulation in forest ecosystems

(Kurz *et al*. 2009). However, there are important limitations to their use, not necessarily specific to empirical G&Y models.

The first of two primary limitations on the application of empirical forest models that will be discussed here is generalizability. A G&Y model calibrated within a specific range of forest conditions should provide accurate and useful results when applied in conditions that are the same or at least very similar (Burkhart and Tomé 2012). This well-recognized limitation applies to the use of models in different conditions and locations from which they were calibrated (Monserud 2003) and requires the calibration of curves within each defined stratum.

The second limitation of empirical model application considered here is that they must be applied at the spatial levels at which they were aggregated. Though less-commonly recognized within forestry literature than generalizability, the issues associated with the downscaled application of models has been studied (e.g., Aertsen *et al*. 2012). G&Y curves are developed using data aggregated from climatologically, geologically, geographically, and biologically distinct areas. In the case of the Nova Scotia Department of Natural Resources and Renewables' (NSDNRR) G&Y curves, the primary, geographically delineating stratum that encapsulates the above factors is the ecoregion (Neily *et al*. 2013). Within each ecoregion, G&Y curves are generated for each observed combination of species mix, crown closure, land capability class, and management history (Table 2.1). These individual characteristics may vary continuously across the landscape but are bounded by and aggregated within each ecoregion. Particularly problematic for our current research is the location of our study area, which is within the Pockwock watershed (Figure 2.1), which straddles the boundary between two ecoregions (Figure 2.2), each defined by a unique climatic regime (Neily *et al*. 2017). Selecting a geographically distinct subset of the total stands within the ecoregion (thus a non-random sample) and expecting this area's growth to resemble the region's mean is a clear example of the ecological fallacy referred to by Alker (1969) as the fallacy of disaggregation. The question then posed by those interested in research or management within a sub-regional unit is how to accurately model a disaggregated area without improper assumptions about the cross scale application of models.

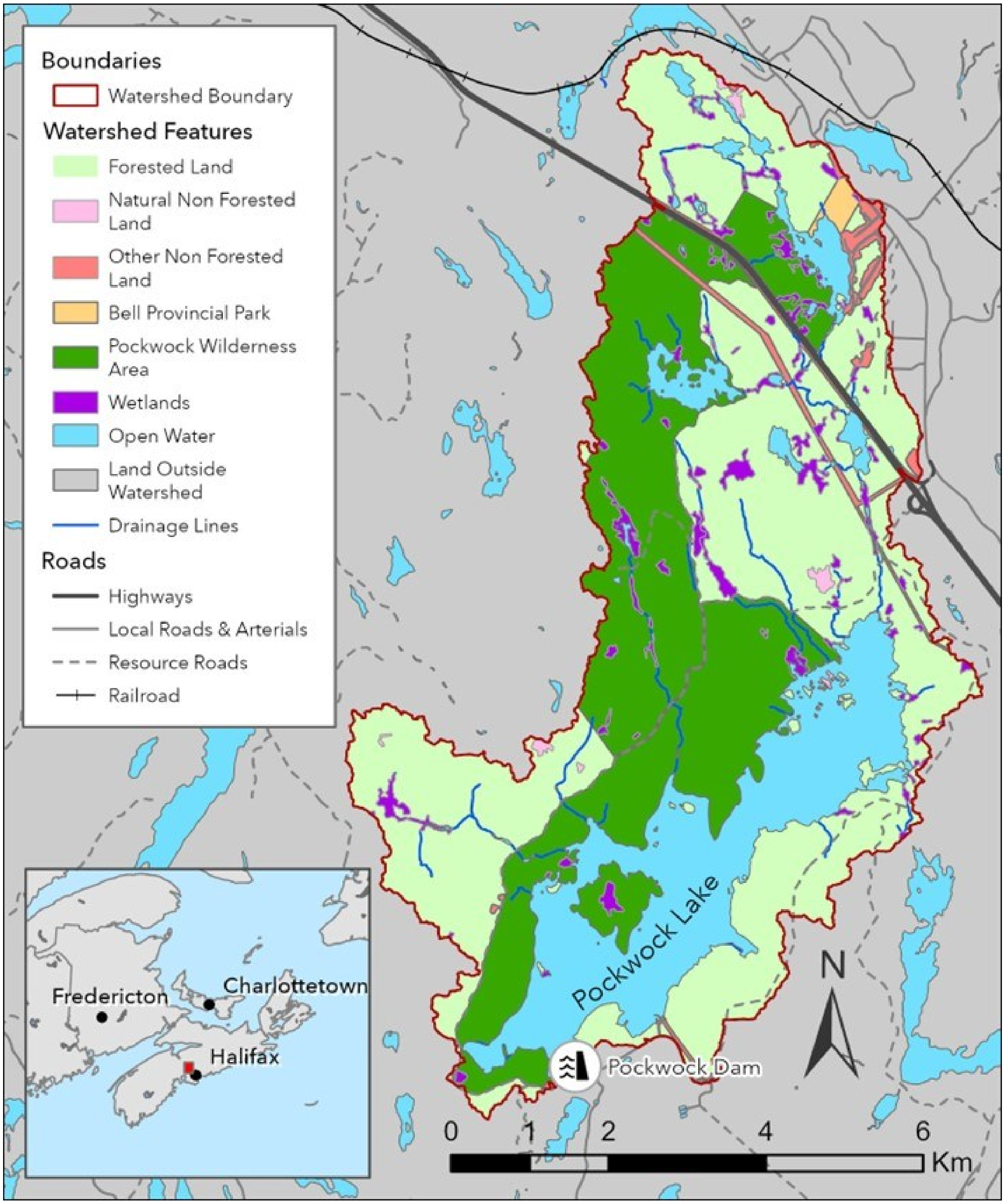


Figure 2.1 Map of the study area, the Pockwock Watershed, including location in proximity to Nova Scotia's capital, Halifax (inset). Data: NS Department of Natural Resources and Renewables; Natural Resources Canada.

In this paper, we attempted to address this issue within a small case-study watershed in Nova Scotia (NS), where work is underway to characterize carbon dynamics. This assessment would benefit from the application of regional G&Y curves, but a cautious approach demands that we validate the use of curves at this spatial level. With a mostly forested area of 4,100 ha, this watershed is too large to characterize in exhaustive detail, as would be possible for a single stand or small property containing only a handful of stands. Alternatively, it is too small to confidently apply the regionally calibrated curves or justify the expenditure of resources to produce new curves. We refer to this middle-ground as a mesoscale forest (as per Clark *et al*. 1998) and our first objective is to evaluate the accuracy of regional growth curves when applied to this forest area. Conversations with local foresters who have worked in the study area revealed that there is an implicit and consistent underestimation of MV from regional yield curves. This could be due to conservative models or inaccuracy when applied at the subregional level, the latter implying that there are other portions of the ecoregion where the regional yield curve would overestimate MV. This, of course, demonstrates the issue associated with applying regional models to the mesoscale and presents a challenge for characterizing the carbon stocks and flows of the area accurately.

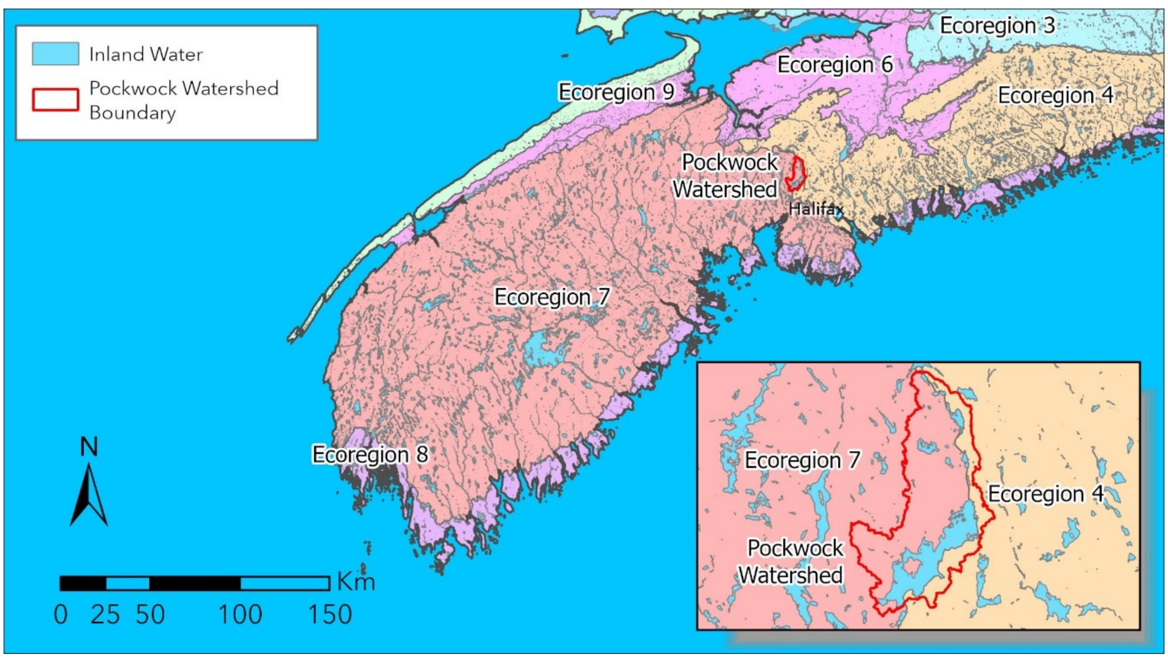


Figure 2.2 Pockwock watershed in relation to Nova Scotia ecoregion boundaries. Inset: focus on Pockwock watershed. Data: NS Department of Natural Resources and Renewables.

Our second objective is to calibrate G&Y curve predictions using field data collected using common mensuration methods to correct inaccuracies when applying regional models at the mesoscale. We endeavor to use existing models and minimal additional data to accurately model forest growth at the mesoscale.

2.2 Methods

2.2.1 Study Area Characteristics

Research is underway in NS, Canada, to characterize and model forest growth in the Halifax Regional Municipality's (HRM) largest water supply, the Pockwock watershed (Figure 2.1). Encompassing 5,400 ha, the watershed's Pockwock Lake supplied an average of 91,583 m3 of potable water per day in 2023 to over 200,000 people in the HRM (Halifax Water 2023). Increasing lake water carbon concentrations are complicating and increasing the costs of water treatment (Anderson *et al*. 2017). This has led the water utility that manages most of the 4,200 ha of primarily forested watershed land to look for a proactive, forest-management-based approach to mitigate future carbon loading. To start a process of forest carbon modelling, we must understand the composition and growth habits of the study forest.

Within the Atlantic Maritime ecozone, NS is strongly influenced by a maritime climate (Wiken *et al*. 1996). The Pockwock watershed sees a mean annual temperature of 6.6 C and a mean of 1,396 mm of annual precipitation (Environment and Climate Change Canada 2024). Part of the Wabanaki-Acadian forest region, forested stands in the study area are predominantly conifer-dominated with red spruce (*Picea rubens* Sarg.) leading, and mixedwood stands including shade-intolerant to tolerant non-conifers where growing conditions allow (Halifax Water 2009).

The Pockwock watershed has been managed for timber values for over 200 years, providing timber for private mills previously situated on the shores of Lake Pockwock. After land appropriation by the provincial government in the 1970s to provide a secure drinking water resource to the growing city of Halifax, the newly acquired Crown land fell under provincial jurisdiction for management. Since public tenure began, the watershed has been managed to protect water quality and treatability through timber harvests and other silvicultural interventions, especially to prevent natural forest disturbances such as fires and large blowdowns (Halifax Water 2009). Most of the watershed is managed by the region's water utility, Halifax Water, whose objective is to provide high-quality water through a multi-barrier approach to drinking water treatment, including environmental management (Halifax Water 2014). Forest harvests are conducted according to Provincial guidelines that are increasingly shifting away from clearcuts and towards ecologically sensitive practices (McGrath *et al.*2021).

2.2.2 Data Collection

Forest characterization took place within a study area of the Pockwock watershed, as defined by five major catchments draining to Pockwock Lake with a total area of 1,400 ha (Figure 2.3). These catchments were of special research interest as this research is connected to efforts to characterize the carbon dynamics of these five catchments. A modified timber cruise method was used to systematically assess the study area with cruise points in a centered grid pattern at a density of 1 point per 2 ha (inset, Figure 2.3). We established a point grid, using ArcGIS Pro (Esri 2019), spaced 141.42 m apart in both north-south and east-west directions. We navigated to each point using Esri Collector (in 2019) and Esri Field Maps (in 2021; Esri 2023) on a mobile phone paired with an Eos Arrow 100 high-precision GNSS device (Eos Positioning Systems 2023). Points that were near natural or anthropogenic boundaries (e.g., stand edge, wet areas, previous harvests, roads) were moved further into the stand in which they primarily fell to improve characterization of the stand, and the point was updated digitally for later reference. Points that were in open water were omitted from the cruise entirely.

Basal area (BA) was determined with the use of a BA factor-2 prism by conducting a single sweep about the point. Species and diameter at breast height (DBH) of each tree within the prism sweep were recorded, diameters measured with a caliper for trees ≤ 65 cm DBH or a diameter tape for trees > 65 cm. Vegetation community, soil parameters, and ecosite classifications were made using the Nova Scotia Forest Ecosystem Classification (FEC) system (Neily *et al*. 2013) to check against similar records in the Crown lands forest model landbase classification (CLFMLC) database (NSDNRR, unpublished dataset). Forest mensuration commenced in spring of 2019 and continued through to the end of summer 2021, capturing pre-harvest conditions throughout the study area. A total of 726 points were assessed in the Pockwock watershed, including 700 forest points with 11,353 living trees over 9 cm in DBH. Excluded points were those that were incapable of growing trees of a merchantable volume such as nutrient-poor bogs or extensive rock outcrops.

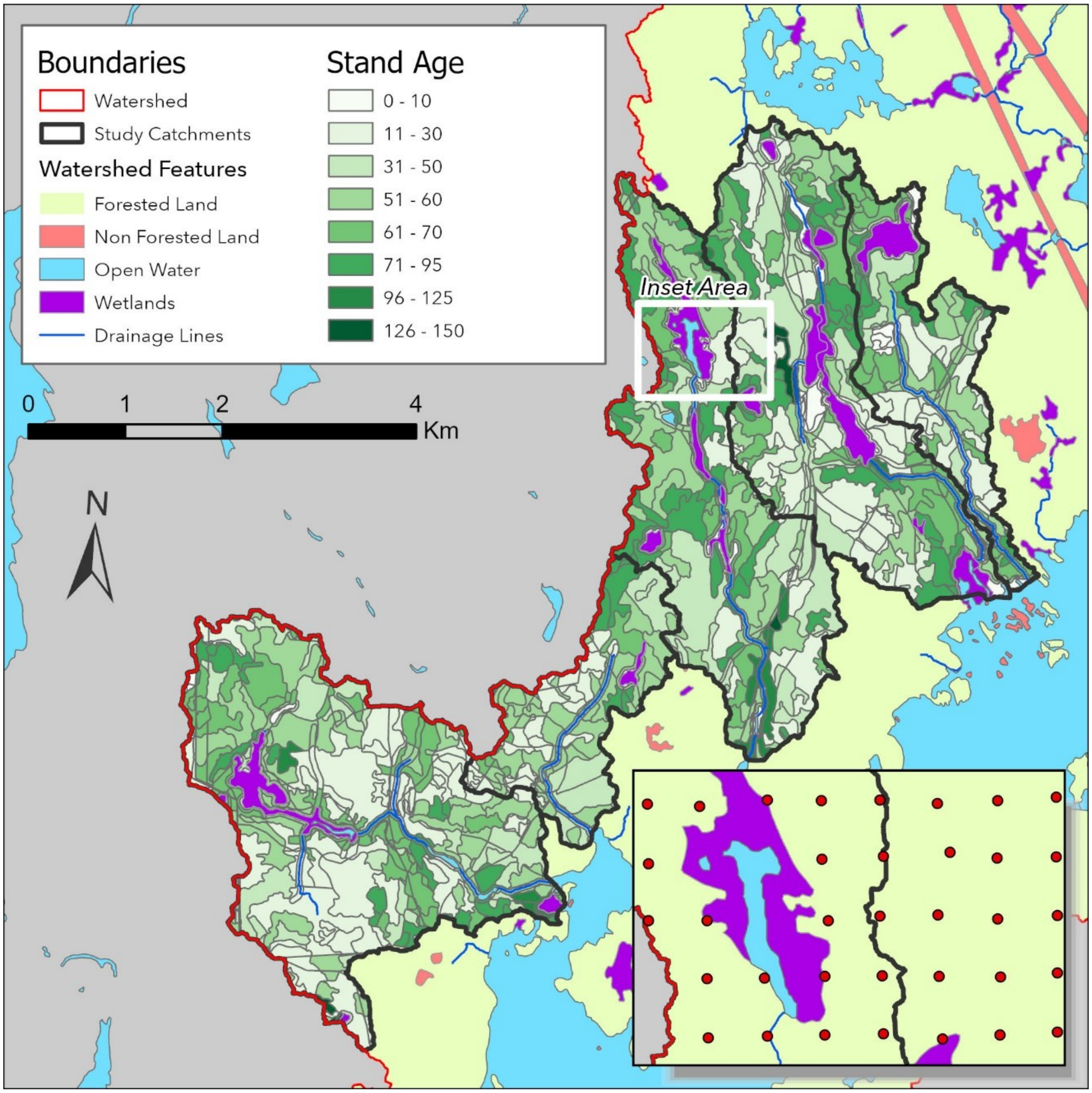


Figure 2.3 Pockwock watershed study area, comprised of five major catchments draining to Pockwock Lake (1,400 ha). Forest stands within the study area are classified by stand age according to provincial records (NSDNRR, unpublished dataset). Inset demonstrates an example of the cruise point grid including points omitted over open water and points moved around natural and anthropogenic features (e.g., non-characteristic barrens or roads).

2.2.3 Other Data Sources & Analysis

The provincial authority on forests in Nova Scotia (NS), the NS Department of Natural Resources and Renewables (NSDNRR), has monitored NS forest growth for several decades. This has included both direct measurements through maintenance of an extensive permanent sample plot programme and remote sensing surveys using aerial imagery, or photogrammetry (Townsend 2003). These plots are spread throughout NS across all Ecoregions. Using this long history of records, forest managers have created a forest inventory and regionally specific G&Y curves that predict stand growth under diverse growing conditions.

Provincial forest inventory data received from NSDNRR included all data necessary for our analysis at the stand level including estimates of stand age, height, crown closure, and several classification strata. The CLFMLC is updated periodically and uses photogrammetry with regular ground-truthing to make classifications at the stand scale. The CLFMLC contains a wide range of information about each stand, but for our purposes, the most important are those that are used to assign a particular G&Y curve. These are ecoregion, forest community, crown closure, land capability class, and management history (Table 2.1).

Table 2.1 Key stand classifiers (among many) in the Crown land forest model landbase classification (CLFMLC) database.

Classifier	Definition
Ecoregion	One of nine ecoregions comprising Nova Scotia based on climate, major physiographic features, and proximity to the ocean, representing areas of 10^4 to 10^6 ha (Neily *et al.* 2017).
Forest community	The relative abundance of softwood and hardwood species and an indication of the leading species proportionally.
Crown closure	Classes of crown closure: • B: 31-50% • C: 51-70% • D: 71-100%
Land capability	The capability for growth in defined classes, assigned as described in NSDNR 2006, in which the class number is centre-point of potential annual productivity in m^3 ha^{-1} yr^{-1}. E.g. LC 5 = 4.6-5.5 m^3 ha^{-1} yr^{-1}
Management history	Stand status based on any management history. Encountered conditions are: • CT/PCT – commercially thinned following pre-commercial thinning • NAE – natural, even-aged stand • NAU – natural, uneven-aged stand • NRG – natural regrowth following harvest • PCT – pre-commercially thinned • PLT – managed as plantation • SELN – previously selection managed

G&Y tables provided by NSDNRR included every feasible permutation of forest classification strata possible in the study area, with estimates of MV at five-year timesteps (NSDNRR 2018, unpublished dataset). Linear interpolation was used to calculate intermediate MVs. Each permutation of characteristics represents a stratum for which a G&Y curve is developed, providing an estimate of stand MV over time from stand initiation. Comparisons between datasets examined MV in m^3 or $m^3\ ha^{-1}$ in all cases.

The imagery for the CLFMLC in the study area was captured in 2013 and 2017, and watershed cruise point field data collection occurred in 2019 and 2021. Age from the CLFMLC was adjusted by the difference in time between when the photo was taken and when field measurements were collected (e.g. if CLFMLC estimated a stand was 35 years old in 2013, when measured in 2019 it would be 41 years old). Stand age is commonly a component of G&Y models but can be an uncertain and tenuous variable both in field data collection and remote sensing alike. Stand age in the CLFMLC data is not an interpreted variable but is instead a function of stand height and mapped LC values (NSDNR 2006), and no attempt was made to validate stand age records in the CLFMLC.

Measurements of BA from cruise-points were compared to assessments of the 700 400 m^2 square (20x20 m) forested research plots within portions of the study area that were to be harvested during the study period. This comparison allowed for validation of the cruise method's MV assessments. Stand MV was calculated from BA using NS-specific MV tables as described in Keys and McGrath (2002). The significance of differences between observed and curve predicted MV was assessed using a Wilcoxon signed rank test due to the non-normal distribution of residuals in the paired data sets. Both cruise point and harvest plot measurements of MV were compared to scale receipts of actual timber harvested. The accuracy of cruise-point and research-plot BA estimates was assessed by comparing the difference between pre- and post-harvest measurements (the portion removed) to scale receipts. We found that MVs measured by the cruise-point method aligned well with scaled amounts, tending towards under-estimating the scaled volume slightly.

2.2.4 Curve Reassignments

Where yield curve MV expectations did not match observed values, new curves were assigned from other G&Y curves developed for the same ecoregion by manipulating two strata definitions that determined curve assignment. This approach avoided generating new curves, which was not feasible given the permutations of conditions observed within the study area. It was favoured over mathematical curve manipulation because it was simpler and ensured that all adjusted growth scenarios would be biologically feasible within the study area, given that they would use existing G&Y curves. Forest communities (species mix) were not changed as this was assumed to be correctly assessed and was corroborated by observations during fieldwork. Two variables that could be manipulated to find better fitting curves within the same region were:

- LC – with classes ranging from 3-7,
- Management state – the management history could be reassigned where it made logical sense based on stand type, observations, historical management records, and in consultation with local managers.

Changes to LC were supported by a comparison of the LC in the CLFMLC to expected productivity based on observations made during fieldwork. The provincial FEC includes likely LC ranges by vegetation and soil types. We determined that many LCs in the CLFMLC were likely underestimated given the relatively high productivity potential of the assessed soil and vegetation type combinations. This showed that the CLFMLC tended to underestimate potential productivity compared to field FEC classifications, especially in less-productive stands (e.g., LC 3-4). Therefore, many stands may be better predicted by remapping yield curves. Changes were made to management state where they were supported by verbal descriptions of management history by responsible parties, especially the primary land manager, Halifax Water (B. Geddes, personal communications, 2021).

2.3 Results

2.3.1 Measured Versus Curve-Predicted Volumes

From the cruise points assessed, 88 unique stratum combinations were identified, within which *n* ranged from 1 to 59 points (Table 2.2). Measured MV at each of 706 cruise points was compared to the MV predicted by the CLFMLC-designated yield curve. Residuals had a right skew (measured MV exceed curve predicted MV) and the mean and median differences (35.8 and 22.3 $m^3\,ha^{-1}$ respectively) indicated that stand MV was generally underestimated by originally assigned curves (Figure 2.4). A Shapiro-Wilk normality test found that the residuals were not distributed normally ($p < 0.001$) and a Wilcoxon signed rank test found that the difference between measured and predicted values (35.8 $m^3\,ha^{-1}$) was significant ($p < 0.001$, Figure 2.5, Figure 2.6).

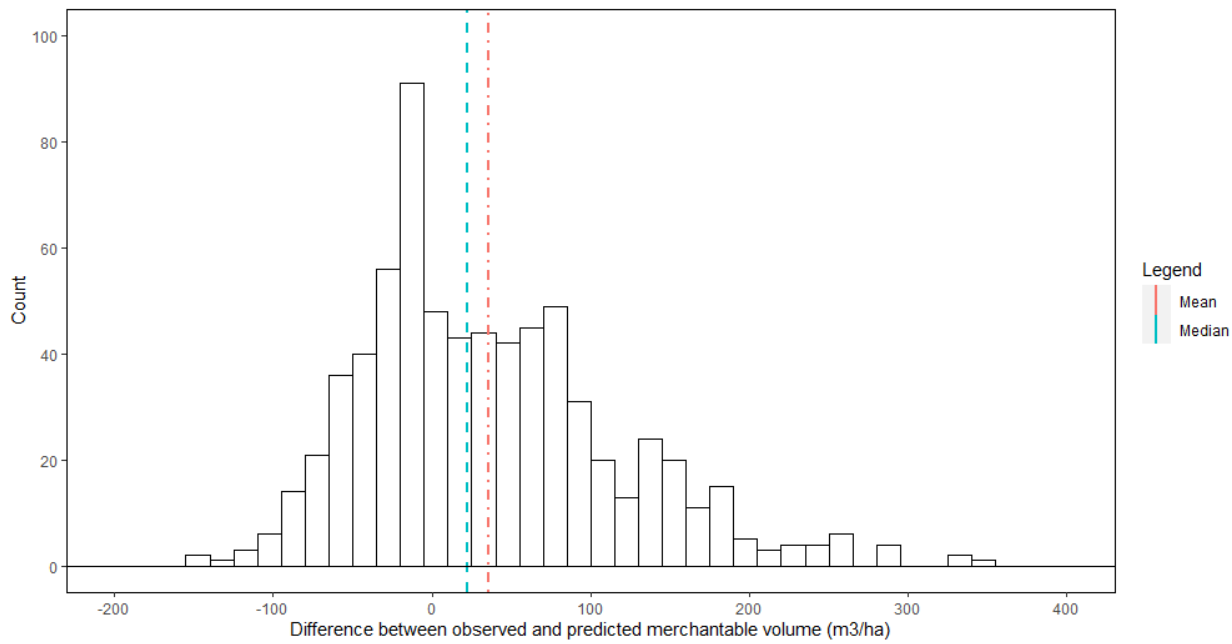


Figure 2.4 Distribution of differences between observed and predicted values for merchantable volume for 700 points measured in the study area. The mean (35.6 m^3 ha^{-1}) is indicated by the red dash-dot line, and the median (22.0 m^3 ha^{-1}) by the blue dash line.

We conducted a comparison of the difference in MV by height and age categories to determine if the residuals were correlated with stand age and height. Height, defined as the average top height of the co-dominant canopy layer (NSDNR 2006), was grouped in 4 m increments of ≤4 m, 4.1-8 m, etc. Age was grouped in 20-year increments from 0-100 years and stands 101-150 years old were grouped in the 150-year class. Height and age benefitted from binning which allowed for more statistically robust comparisons. This analysis revealed that as a stand gains height, the difference between observed and predicted MV generally increases, and as a stand gets older, the difference increases until the 100-year class, then residual patterns become less predictable (Figure 2.6).

Table 2.2 Summary of forest strata captured in 700 forested cruise points in the Pockwock watershed study area. Stratum is defined by crown closure, land capability class (LC), management history, and forest community (see Table 2.1 for stratum definitions).

Stratum (Crown closure – LC – management history)	Intolerant hardwood	Mixedwood - intolerant hardwood leading	Mixedwood - softwood leading	Mixedwood - tolerant hardwood leading	Pine & spruce dominated	Red spruce & balsam fir dominated	Red spruce plantation	Red/black spruce dominated	Spruce & balsam fir dominated	Spruce, pine, hemlock	Tolerant hardwood	Total
B-3-NAE		2	1			1		33				**37**
B-3-NAU		1	3			1		24				**29**
B-3-NRG									1			**1**
B-4-NAE						6		33		3		**42**
B-4-NAU		1	2			2		2				**7**
B-4-NRG								1				**1**
B-5-NAE		1	1		3			20	1	1		**27**
B-5-NRG						2						**2**
B-6-NAE		2	3					18			2	**25**
C-3-NAE						2		2				**4**
C-4-NAE			1			5		27				**33**
C-4-NAU			2			1		6				**9**
C-4-NRG			3					2				**5**
C-5-NAE		4	10			26		59				**99**
C-5-NAU						3		6		5		**14**
C-5-NRG			4			16		2				**22**
C-6-NAE			3					41				**44**
C-6-NAU			1			7		7				**15**
C-6-NRG	1							9				**10**
D-3-NRG			1					3	6			**10**
D-4-NRG			33	2		1		13	3			**52**
D-5-CT/PCT								12				**12**
D-5-NAE			3					9				**12**
D-5-NRG	7	4	19	3		2		5	1			**41**
D-5-PCT				6					6			**12**
D-5-SELN			5					13				**18**
D-6-CT/PCT								15				**15**
D-6-NAE								9				**9**
D-6-NRG	18	19	22					7				**66**
D-6-PCT	1							3	10			**14**
D-6-PLT							2					**2**
D-6-SELN			11									**11**
Total	**27**	**34**	**128**	**11**	**3**	**75**	**2**	**381**	**28**	**9**	**2**	**700**

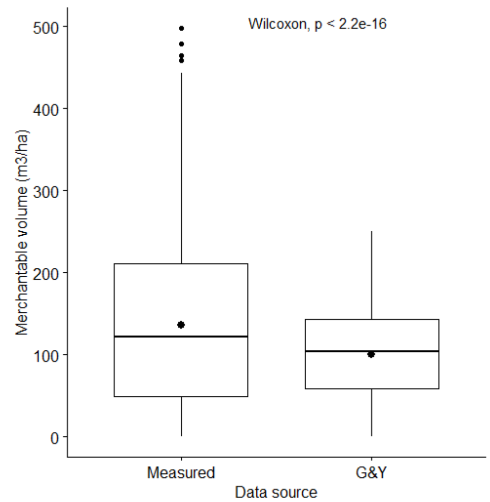


Figure 2.5 Distribution of merchantable volume from field measurements and estimates from growth and yield curves based on landscape stratification. The mean and median of measured values (136.6 m^3 and 123.7 m^3, circle and line within the box respectively) are higher than the mean and median of growth and yield predicted values (100.8 m^3 and 104.0 m^3). A paired Wilcoxon signed rank test finds this difference significant.

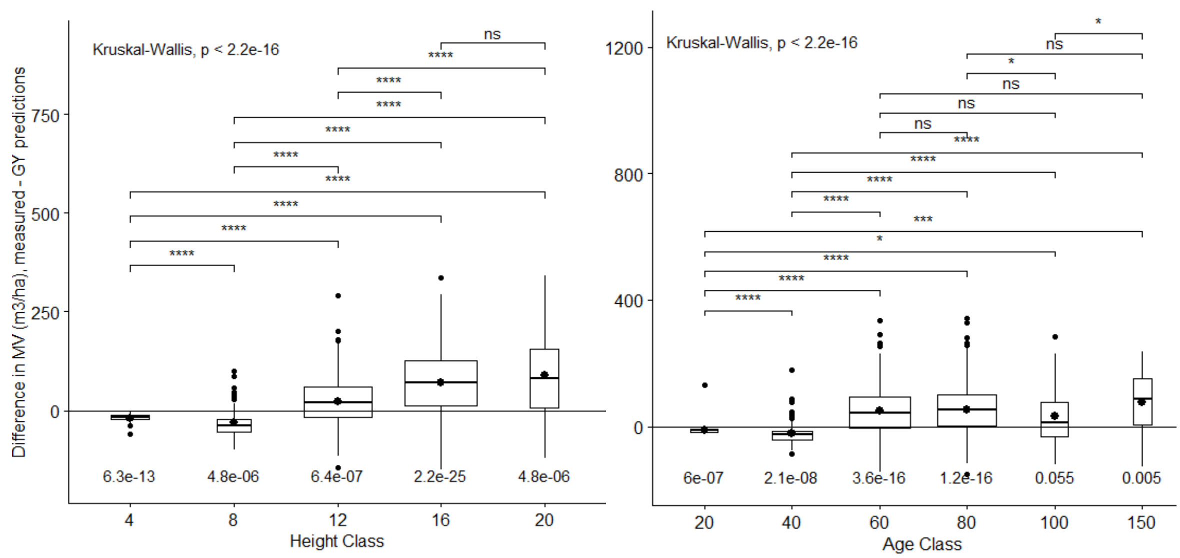


*Figure 2.6 Comparison of the differences between measured and estimates of merchantable volume from growth and yield curves by stand developmental stage, including height and age. Box width corresponds to the proportion of the total population contained within each class where wider is a higher proportion; the results of a single Wilcox signed rank test for each group against mu = 0 are displayed along the x-axis; the single circle within each box is the group mean. Significance values of p for comparisons between classes are: ns > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001, **** ≤ 0.0001*

LC class was one of the strata targeted for reassignment based on the findings of these comparisons. A pattern in differences between observed and predicted MV would be useful to determine how curves should be reassigned to better predict MV. Merchantable volume in stands classified as LC 3, 4, and 5 were all different from LC 6, and a

Wilcoxon signed rank test found that LC classes 3, 4, and 6 all had a significant difference (Figure 2.7). Stands with an LC of 6, the most productive and numerous class in the study area, were also the most underestimated by curves and this residual became a focus for curve reassignments.

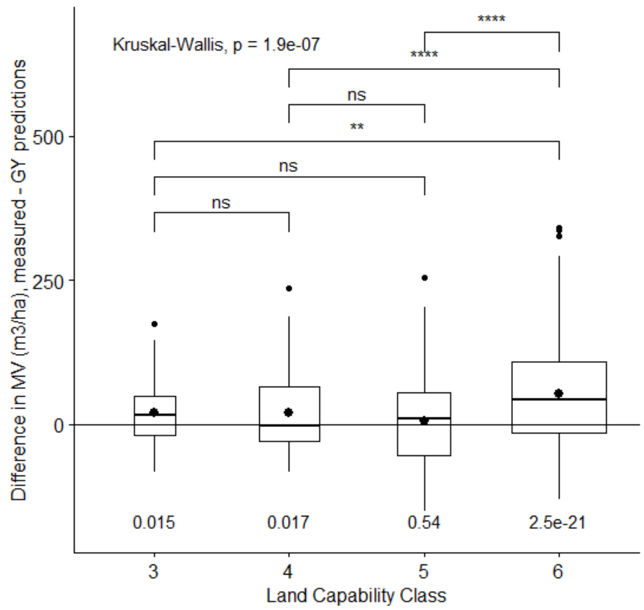


*Figure 2.7 Comparison of the differences between measured and predicted estimates of merchantable volume by land capability class using a Kruskal-Wallis test. Box width corresponds to the proportion of the total population contained within each class where wider is a higher proportion; the results of a single Wilcox signed rank test for each group against mu = 0 are displayed along the x-axis. Significance values of p for comparisons between classes are: ns > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001, **** ≤ 0.0001*

Finally, we compared the differences by forest communities to determine if any were more frequently under- or over-estimated than others. We found that MVs in two forest communities were significantly under-estimated by the default curves compared to observed field data (SRSBSDOM and SSPBFDOM, Figure 2.8, see figure for classification definitions), and one group was significantly over-estimated (SBFDOM, Figure 2.8). These results were used to hone curve reassignments by modifying LC of specific forest communities to minimize residuals, selecting higher LC where the curve underestimated MV, and lower LC where overestimated. Based on all the above findings, certain strata were reassigned to different G&Y curves to better predict MV accumulation.

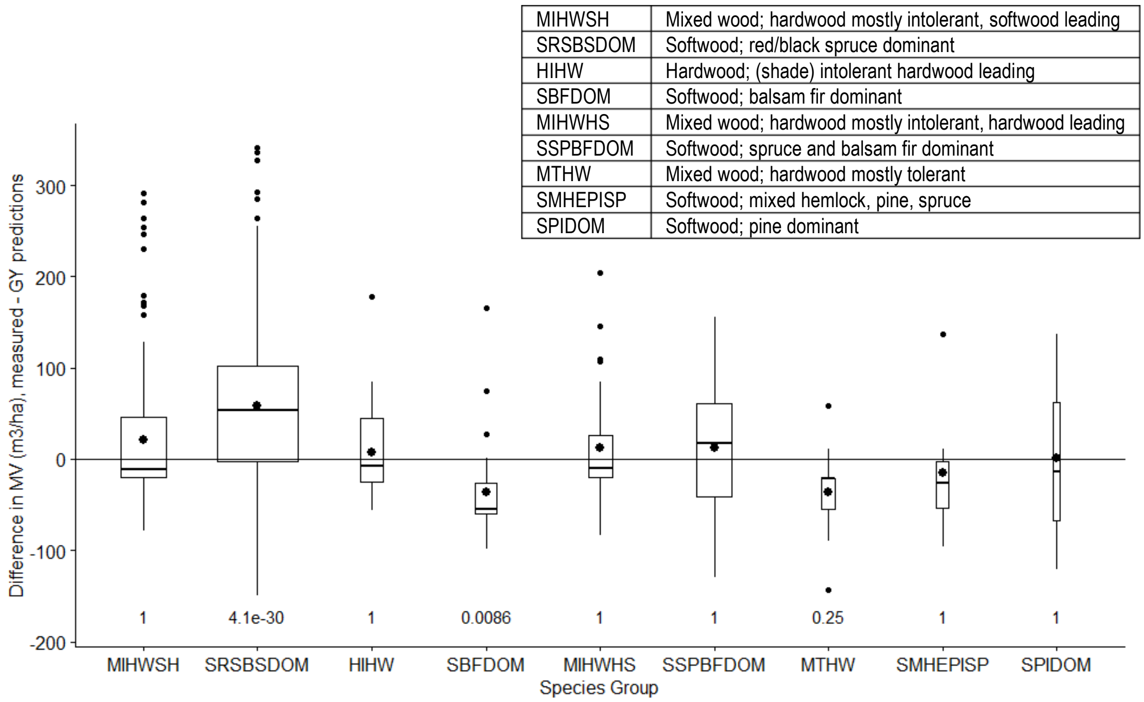


Figure 2.8 Comparison of the differences between measured and predicted estimates of merchantable volume by forest community. Box width corresponds to the proportion of the total population contained within each class where wider is a higher proportion; the mean of groups is indicated by the circle within each box. The results of a single Wilcox signed rank test for each group against mu = 0 are displayed along the x-axis.

2.3.2 Yield Curve Reassignment

Ecosite assessments made during fieldwork using the provincial FEC provide a range of likely LC values for each site, thus a point of comparison for the CLFMLC LC dataset. While the CLFMLC LC values provide good estimates for planning at the regional level, a detailed field assessment of conditions should provide better estimation at the mesoscale. This comparison showed that both CLFMLC and field assessment agree on classification of more-productive sites (i.e., LC 6), but the CLFMLC predicted less-productive and uneven-aged sites to have lower LC than was found through field measurements (e.g., LC 3 in CLFMLC field-assessed as likely LC 4). This is especially relevant for understanding instances where the CLFMLC predicts stands with LCs not commonly associated with the conditions found in our study area, such as red spruce-eastern hemlock (spruce-hemlock) stands on LC 3. This forest community rarely has an LC as low as 3, and generally not in the types of soils found in the Pockwock Watershed (Neily *et al*. 2013). This trend suggested that residuals, especially for certain forest communities, may be reduced by increasing the LC used in curve assignment.

Based on the above understanding of LC, red/black spruce (SRSBSDOM) and shade-intolerant mixedwood (MIHWSH & MIHWHS) stands, as well as all uneven-aged stands were promoted by one LC to a maximum of 6, the highest LC recommended for conditions and forest communities in the study area (Neily *et al*. 2013). Conversely, balsam-fir-dominated stands (SBFDOM) tended to be overestimated and a reduction in LC was applied to compensate for this.

Consultation with the watershed forest manager revealed that while the CLFMLC listed most of the stands in this area as even-aged or in an unmanaged (post-harvest) state, this was likely not the case (B. Geddes, personal communication, 2021). Silvicultural treatments conducted before digital record-keeping (which started in the early 2000s) were not reflected in the provincial inventory of the study area. The manager suggested that any appropriately aged stands with a high proportion of softwood should be assumed to have been pre-commercially thinned (PCT). Thus, these forest communities were changed from either unmanaged (post harvest) or even-aged status to PCT. Because PCT increases MV yields (Homyack *et al*. 2004; Zhang *et al*. 2006), this change had a substantial effect on the predicted MV accumulation.

No changes were made to curve assignments for stands in forest communities SPIDOM, SMHEPISP, MTHW, or HIHW (see Figure 2.8 for group descriptions). This was due to low sample size providing poor confidence in adjusting assignments, or due to the default curves predicting MV well compared to observations as indicated by results of Wilcoxon signed rank test (Figure 2.8).

After applying curve reassignments and reassessing predicted values, the difference between measured and curve predicted values was significantly lower. While still a right-skewed distribution of differences, the mean and median shifted to 7.3 and -6.7 m^3/ha respectively (Figure 2.9). The data were more normally distributed about 0, but a Shapiro-Wilk test found that although the distribution shifted (Figure 2.10), it remained significantly not normal ($p < 0.001$). A Wilcoxon signed rank test found the residuals no longer significant ($p = 0.45$, Figure 2.11).

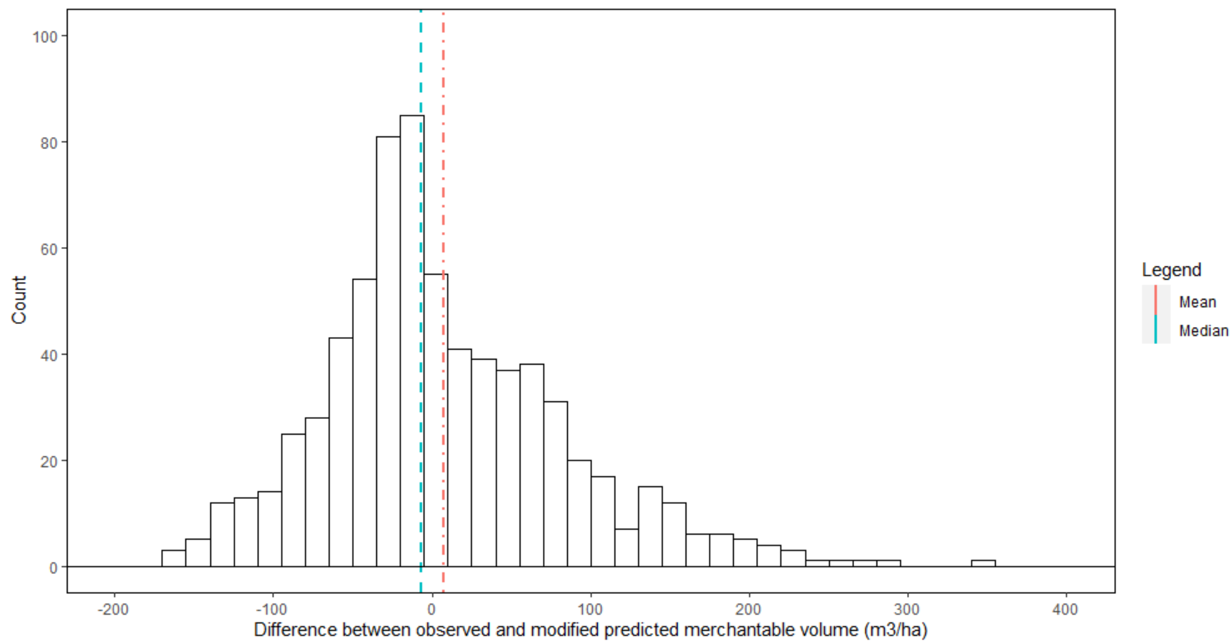


Figure 2.9 Distribution of differences between observed and modified predicted values for merchantable volume for 700 points measured in the study area. The mean (7.3 m^3/ha) is indicated by the dash-dot red line, and the median (-6.7 m^3 ha^{-1}) by the dashed blue line.

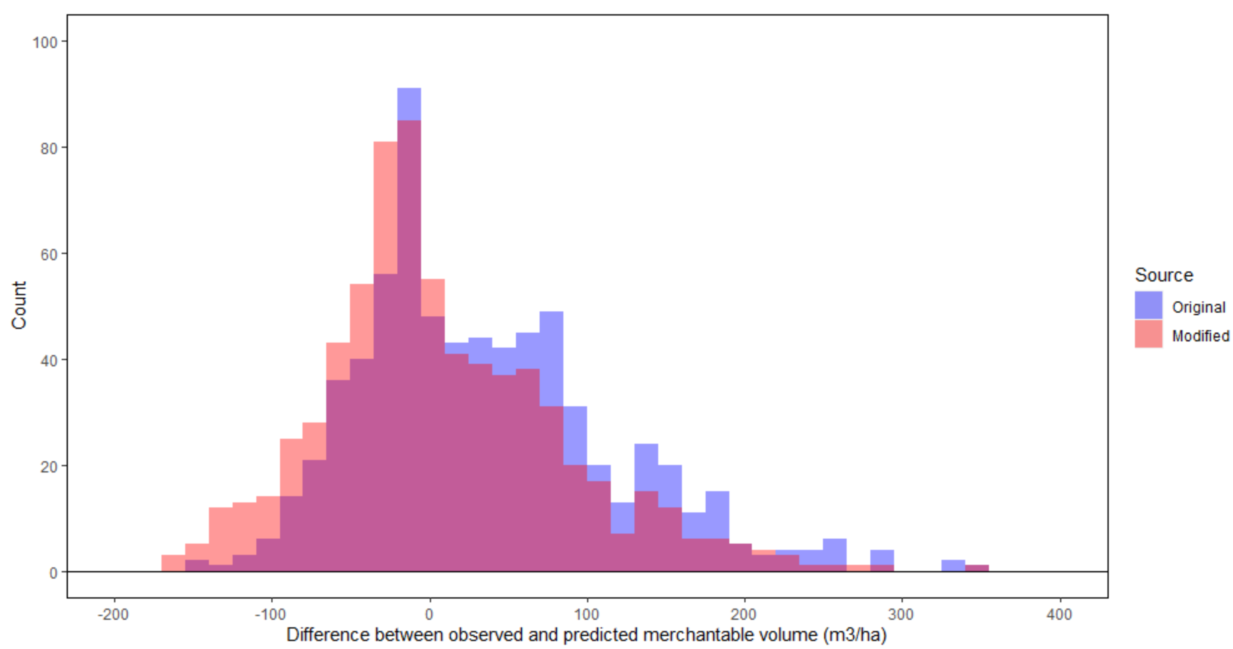


Figure 2.10 Comparison of the difference between observed merchantable volume (MV) to predictions of MV from original yield curves assigned from provincial inventory data, versus predictions of MV from modified yield curve assignments, in m^3 ha^{-1}. Blue columns are the original differences, red are differences from modified yield curve assignments, and where they overlap is a combination of the two colours.

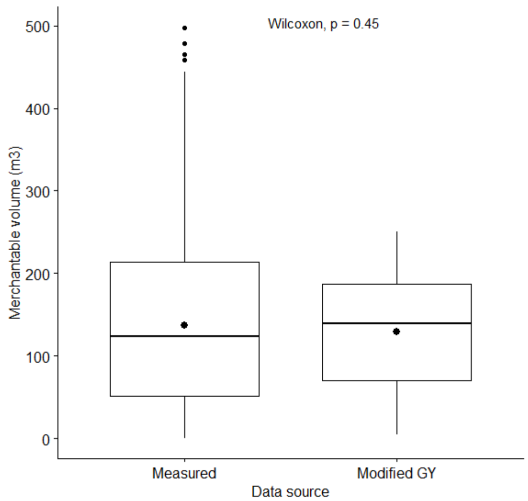


Figure 2.11 Distribution of merchantable volume from field measurements and estimates from growth and yield curves based on modified landscape stratification. The mean of measured values (136.6 m^3, circle within the box) is still higher than the mean of growth and yield (G&Y) predicted values (129.0 m^3), like original results, but the median of measured values (123.7 m^3, line within the box) is now less than the median of G&Y predicted values (139.2 m^3), the opposite of the original results. A paired Wilcoxon signed rank test finds this difference not significant.

2.3.3 Measured Versus Modified Curve Predicted Volumes

Compared to estimates of MV from default curve assignments, the newly assigned curves had several impacts on the residuals when grouping stands by age, height, LC, and forest community. Grouped by age category, reassigned curve residuals generally decreased (Figure 2.12), with fewer significant differences between groups compared to the original curve predictions (Figure 2.6). Grouping by height, however, did not show a similar trend. Evaluation of differences by LC was important for understanding how to reassign curves and the pattern of residuals changed substantially from the original curve assignments. Measured versus estimated values for LC 3 and LC 4 were no longer significantly different (Figure 2.7, Figure 2.13). While LC 6 was still significantly different, the magnitude of the difference decreased. On the other hand, the residual for LC 5 increased to the point where modified estimates significantly overestimated MV, whereas the difference was not previously significant.

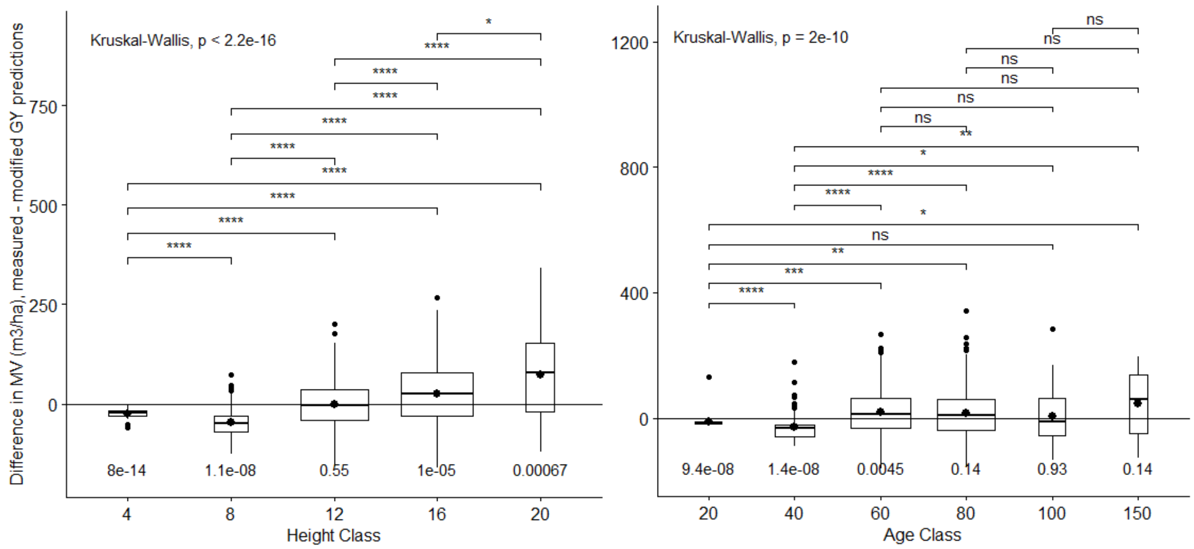


*Figure 2.12 Comparison of the differences between measured and modified estimates of merchantable volume from growth and yield curves by stand developmental stage, including height and age. Box width corresponds to the proportion of the total population contained within each class where wider is a higher proportion; the results of a single Wilcox signed rank test for each group against mu = 0 are displayed along the x-axis; the single circle within each box is the group mean. Significance values of p for comparisons between classes are: ns > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001, **** ≤ 0.0001*

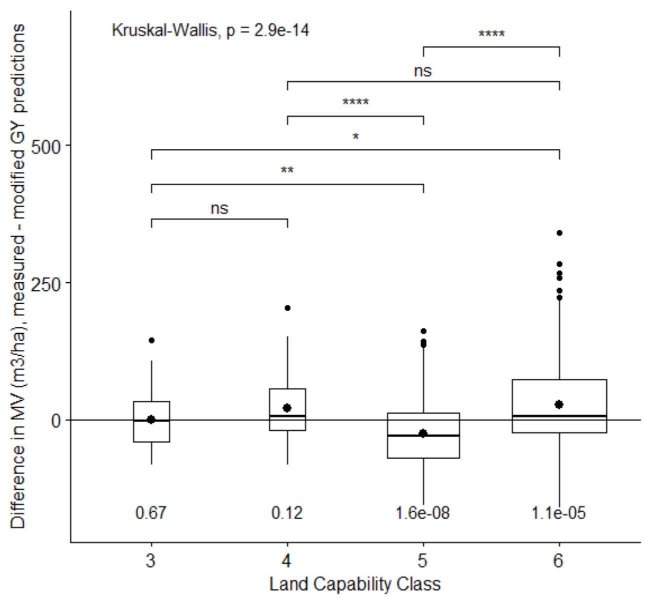
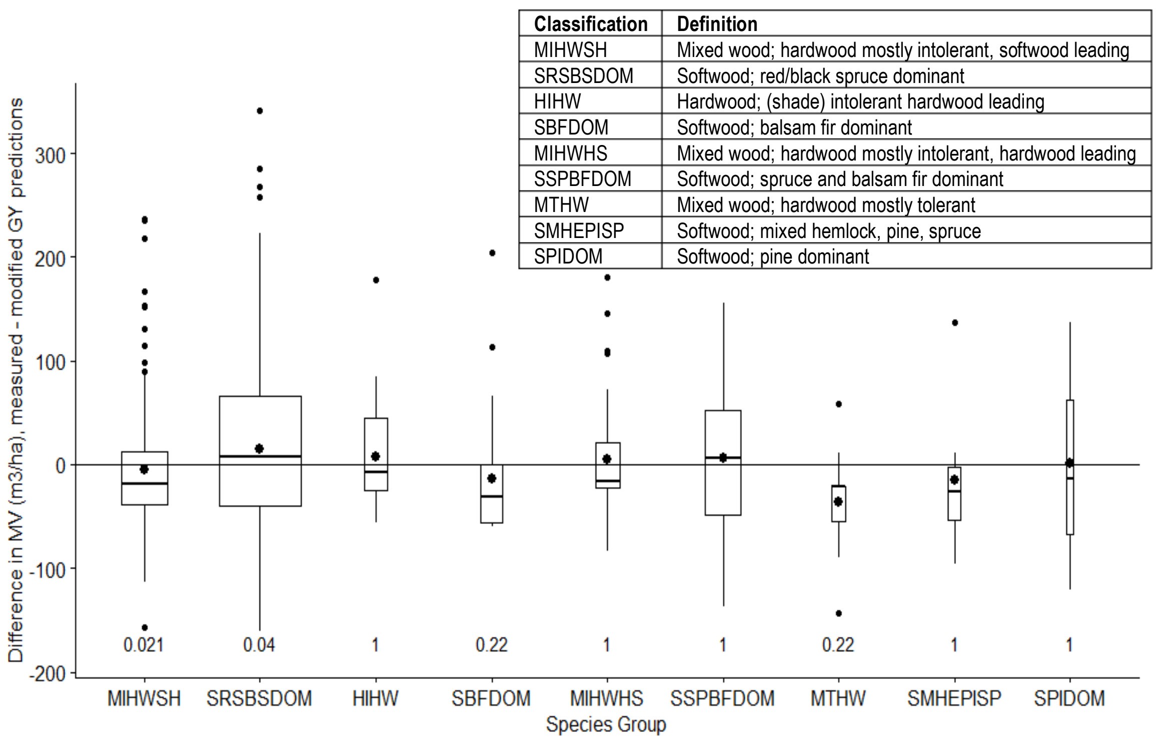


*Figure 2.13 Comparison of the differences between measured and modified predicted estimates of merchantable volume by land capability class using a Kruskal-Wallis test. Box width corresponds to the proportion of the total population contained within each class where wider is a higher proportion; the results of a single Wilcox signed rank test for each group against mu = 0 are displayed along the x-axis. Significance values of p for comparisons between classes are: ns > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001, **** ≤ 0.0001*

Analysing differences by forest community was useful in determining where to focus rules for curve reassignment, and re-analysis determined if the process reduced differences by group. The forest communities that were specifically targeted in the rules changed as expected (Figure 2.14). Most notably, the Wilcoxon signed rank test showed that curve changes for SRSBSDOM brought predictions substantially closer to measurements ($p < 0.001$ to $p = 0.04$). Similarly, SBFDOM predictions were significantly closer to measurements ($p < 0.001$ to $p = 0.22$). Predictions worsened for MIHWSH and MTHW, both seeing increases to predicted yields that exceeded measured values. This was due to an increase in LC for most uneven-aged stands, and in the case of MIHWSH, also by changing management status to PCT. These results are a substantial improvement overall, though some individual classes analyzed did show decreases in prediction accuracy, and what differences remain may be due to factors that cannot be controlled for within the scope of the current research.



Classification	Definition
MIHWSH	Mixed wood; hardwood mostly intolerant, softwood leading
SRSBSDOM	Softwood; red/black spruce dominant
HIHW	Hardwood; (shade) intolerant hardwood leading
SBFDOM	Softwood; balsam fir dominant
MIHWHS	Mixed wood; hardwood mostly intolerant, hardwood leading
SSPBFDOM	Softwood; spruce and balsam fir dominant
MTHW	Mixed wood; hardwood mostly tolerant
SMHEPISP	Softwood; mixed hemlock, pine, spruce
SPIDOM	Softwood; pine dominant

Figure 2.14 Comparison of the differences between measured and modified predicted estimates of merchantable volume by forest community. Box width corresponds to the proportion of the total population contained within each class where wider is a higher proportion; the mean of groups is indicated by the circle within each box. The results of a single Wilcox signed rank test for each group against mu = 0 are displayed

2.4 Discussion

Although there was a wide distribution of residuals between observed and yield curve predicted MVs, changing curve assignments based on more accurate site-specific data resulted in a significantly more accurate estimate of current stand MV from provincial inventory data. This resulted from only two changes in the application of regional G&Y curves to a remotely sensed data set. First, targeting forest communities and LC classes where residuals were the highest resulted in notable improvements in model estimates of MV. Though the prediction accuracy of some classes analyzed did decrease, the overall change in median residual and distribution improved (Figure 2.9). Secondly, changing the management state based on local knowledge of forest managers improved results by better modelling the forest conditions. This second change demonstrates an advantage of working at the mesoscale (or smaller) area, in which the landscape can be described by on-the-ground managers and inventory classification errors can be identified and addressed. These two changes represent curve reassignments and not curve modifications, which is another approach that could be applied in instances where modelled results consistently differ from observations.

An alternative to curve reassignment is to multiply the curve uniformly by an appropriate factor to compensate for the residual and create a curve that matches observations (e.g., Hökkä and Groot 1999; Shater *et al*. 2011). In an attempt at such calibration of growth models, Stage (1973) adjusted curve growth rates with the assumption that the overall shape was correct thus pioneering self-calibrating growth models, but warned that “[g]rowth functions should be based on data derived from the area to which the model is to be applied” (Stage 1973). Clark and Avery (1976) similarly warned against assuming that relationships will exhibit the same pattern and magnitude at different spatial levels. An auto-calibration method could have been applied in this study and may have produced new yield curves that predict MV even better from the inventory at the mesoscale. However, the simplicity of a curve re-assignment process makes it appealing to those who might manage at the mesoscale. Additionally, reassigning stands to alternative, existing curves grounded model predictions in conditions and growth patterns found within the same ecoregion and ensured that models made biologically appropriate estimates accounting for within-region variability based on landscape factors not included in curve assignment.

Nova Scotia G&Y models are matched to stands based on five landscape variables: ecoregion, species mix, LC, canopy closure, and management history. There is, however, a much wider range of landscape variables that affect forest site productivity. Many such variables are assessed and recorded as part of routine forest management or research or are readily available through other sources. Some examples include sub-regional precipitation levels, slope position and aspect, soil chemistry and characteristics, underlying geology, and drainage class. Aggregating data spatially to scale up models will reduce modelled landscape heterogeneity (Levin 1992; Cao and Lam 1997), and result in information loss as landscape factors such as those above are omitted when producing regional models (Meentemeyer and Box 1987). This is a necessary trade-off between model accuracy and data requirements, with the ultimate objective of producing useful models with reasonable data requirements.

One potential alternative to predict forest growth at the mesoscale is to apply process models that can account for a variety of landscape factors. A key benefit to process models is the ability to incorporate the effects of changing system variables, such as changes in temperature and precipitation regime that will affect tree growth. This is in fact a key limitation of empirical models, which generally cannot be extended past observed conditions. On the other hand, two issues with utilizing process models at this level are their accuracy, especially when input data are of poor quality, and the utility of these models to managers. While Ashraf *et al*. (2012) found that a well-calibrated process model can make better G&Y predictions than the NS empirical model (O'Keefe and McGrath 2006), their predictions were best when modelling intensely-studied forest stands. They found that model accuracy was highly sensitive to input data quality for a range of variables. Additionally, most non-government forest managers operate at a sub-regional level and lack the resources to calibrate novel models and generate new curves. Heeding Vanclay's (1994) admonition that models be both useful to and usable by those who manage forests, favouring empirical G&Y models limits data requirements to what is both familiar and readily available to those who manage. Therefore, this method of calibrating regional yield curves to the mesoscale presents a useful tool for managers to better understand forest conditions and growth from regional inventories.

Further use of empirical models in this way would benefit from methodological improvement beyond what was exercised in this research, especially to be resilient to changing forestry practices. The aerial photogrammetry upon which the provincial forest inventory is based allows a confident estimation of physical stand characteristics such as height and stocking in even-aged stands (NSDNR 2006). However, G&Y curves use stand age to predict MV, a variable that cannot be directly viewed from images. Age is instead determined based on the time since last known stand-replacing disturbance, natural or anthropogenic, or an estimate calculated based on the stand height and LC (NSDNR 2006). Both methods have drawbacks including the requirement for accurate harvest and natural disturbance records, and variance in correlation between stand age and height (e.g., NSDLF 1987), error that is compounded by imperfect estimates of height from air photos (Mowrer and Frayer 1986). Additionally, the continuation of even-aged stand management is increasingly fraught as society increasingly demands uneven-aged management strategies (Lahey 2018). Rather than assigning stands to yield curves based on age, matching directly on current biomass or MV would eliminate the error due to age calculations. Alternatively, methods that use air photos and LiDAR show promise in assessing stand metrics and helping to determine stand age and place on a yield curve (Véga and St-Onge 2008; Véga and St-Onge 2009; Fu *et al*. 2018), including in uneven-aged stands (Jayathunga *et al*. 2019), though acquiring LiDAR data and deriving enhanced forest inventory data remains relatively expensive.

In this study, we examined the accuracy of regional, empirical growth models to determine stand MV in a small, forested watershed. Matching stands to growth curves was based on a variety of landscape characteristics from the provincial forest inventory, and position on the curve was determined from inventory age data. We compared these estimates to measurements of MV at 700 cruise points and found that the regional growth curves significantly underestimated MV. Through consultation with local forest managers and an examination of the differences, yield curve assignments were changed through altering LC and management history variables. These changes resulted in curves predicting current MV with no significant difference compared to field measurements.

Through this assessment, we demonstrated the importance of applying models at the spatial level at which they were developed. G&Y curves for strata within an ecoregion are based on stands in a wide but acceptable range of conditions but applying these curves to only a small piece of this ecoregion is a form of ecological fallacy that may produce unreliable predictions of stand MV. Though ideally such curves could be developed at any spatial level, the data requirements exceed the capacity of most land managers. Calibrating assignment of regional curves offers forest managers a way to understand current conditions of a mesoscale forest with familiar and minimal additional data requirements. Although data collection for this study was extensive, careful landscape analysis before fieldwork would allow targeting the most dominant stand types to maximize effect on accuracy with limited resources. Managers can compare observations of a forested landscape to yield curve expectations and adjust yield curve assignment to ensure a good fit between expected and observed MV.

Further work is required on this method of downscaling regional models to increase accuracy, including perhaps using biophysical variables as well as age to place stands on growth curves. Additionally, new technologies and techniques using LiDAR and time series of aerial imagery may help to better assess uneven-aged stand metrics. Forest managers are a diverse group who manage widely ranging forests often with vastly different management philosophies and practices, and there is no model that can suit everyone’s needs at once (Landsberg 2003). However, despite this, and the inability to account for climate change, regional models offer good understanding of the growth trajectory of forests, and managers can use our calibrated approach to more accurately predict the future of their mesoscale forests.

Chapter 2 References

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3 Where Does Carbon Go?

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Abstract

While forest management commonly seeks to increase carbon (C) capture and sequestration, in some settings, a high density of C storage may be detrimental to other land uses and ecosystem services. We study a forested, drinking-water-supply watershed to determine the effects of forest management on C storage with the implicit understanding that greater storage of C will lead to increased quantity of carbon exported hydrologically into a source-water reservoir. Using a custom implementation of CBM-CFS3, a Canadian model to simulate C transformations and movement in forested systems, and a custom forest disturbance and management model, we simulate various management scenarios and their C outcomes. The largest forest C pool, mineral soils, is very slow to change and manipulating DOC export through this pool would likely not be feasible within human management timescales. Other pools, in which C has lower residence time and from which C is more readily mobilized, are a more promising area for future research into hydrologic DOC export under varying management regimes. Our findings indicate that management activities can serve to reduce forest C storage, but further research is required to connect these outcomes to hydrologic export.

3.1 Introduction

3.1.1 Forest Carbon

Forests play a vital role in the global carbon (C) cycle, in which C storage is valued for contributions to mitigating increasing atmospheric C concentrations. Ample research has examined the relationship between forests and their capacity to store C, including the relationship between forest management and relative storage (Cooper 1983; Harmon *et al*. 2011; Hoover 2011; Mäkipää *et al*. 2023). Forest C capture and storage is not a study of static pools, but of highly dynamic transfers between pools, and management interventions act both directly and indirectly to influence the magnitude of these transfers.

The most visible – and easily influenced – forest C pool is living biomass including all living parts of a tree both above and belowground, estimated at 363 +/- 28 Pg globally (Pan *et al*. 2011). Whether through natural or anthropogenic means, C in living biomass inevitably either becomes dead organic matter (DOM) or is exported from the landscape (by human intervention or otherwise, e.g., fire). The C in DOM begins a process of transformation and exchange between pools differentiated by both location and physical and chemical properties. The DOM pool that stores the most C and for the longest time is soil organic C (SOC). This pool is estimated (to 1 m depth) at 383 +/- 30 Pg globally (Pan *et al*. 2011), representing an estimated average of 44% of a forest's total C storage.

Estimating and predicting the movement of C in and out of these pools is accomplished by a range of forest C models such as CBM-CFS3 (Kurz *et al*. 2009), CO2FIX (Schelhaas *et al*. 2004), CASMOFOR (Somogyi 2019), and more. These models either integrate or rely on the outputs of separate forest growth models to predict forest growth in response to natural conditions and management interventions. The study of forest C storage, commonly using such models, is often done with the intent to realize maximum atmospheric C sequestration in the face of a changing climate. However, not all C is exported from forest landscapes directly to the atmosphere. C movement within soils is closely linked to hydrologic fluxes which serves not only to move it vertically down through the soil column, but also laterally through forest soils to receiving water systems as dissolved organic carbon (DOC) (Michalzik *et al*. 2001; Neff and Asner 2001).

3.1.2 DOC Management in a Forested Water Supply

The global sum of terrestrial C lost to inland water is poorly characterized; however, work to estimate hydrologic C export finds that approximately 15% of terrestrial net ecosystem productivity (NEP) is leached as DOC (Nakhavali *et al*. 2021) and estimates of total losses are as high as 5.1 Pg annually (Drake *et al*. 2018). Carbon is dissolved as water moves vertically and laterally through soils, then following hydrologic flow paths and performing important environmental functions along the way (McDowell and Wood 1984). Dissolved organic carbon movement is an important mass transfer mechanism in the global C cycle between terrestrial and aquatic environments (Hope *et al*. 1994), and is linked to transport of minerals and metals with C-rich, acidic solutions (Lawlor and Tipping 2003). The reddish-brown colour of organic compounds added to water provides ultraviolet protection for aquatic life (Schindler 1971). However, DOC concentrations are increasing in many parts of the world due to a confluence of factors (Evans *et al*. 2005), and causing issues where water is destined to be consumed by humans.

Dissolved organic carbon in a drinking water supply must be removed before treatment to prevent formation of disinfection byproducts that are harmful to human health (Davies and Mazumder 2003). This is accomplished in many source water plants by flocculation, pulling C out of solution by introducing coagulating chemicals (Matilainen *et al*. 2010). After separation, the water is left clear, and a sludge of C and other compounds is extracted for disposal. Increased DOC requires more coagulant, more time to separate, and more filtration capacity to remove the flocculant from the water (Xu *et al*. 2016). While treatment plants can be built to handle this problem, continual increases in DOC have necessitated expensive plant upgrades. Watershed managers in one forested drinking water supply are seeking a proactive approach to mitigate C loading in source waters through forest management interventions to reduce the need for future treatment plant expansions.

3.1.3 Research Objectives

In this research, we sought to better understand the relationship between forest management and relative C accumulation in forest soils of the Pockwock watershed, in Nova Scotia (NS), Canada. The purpose of our research is to quantify the effect that management actions can have on both short- and long-term forest C storage. Future work will link these findings to hydrologic export through hydrologic modelling. The first objective is to determine to what degree harvest type and intensity affects C accumulation in forest soils. The second objective is to examine how natural disturbance management alone, or in combination with planned harvests, can affect C accumulation at the watershed level. We endeavour to provide watershed managers with a better understanding of how forest management decisions affect long-term C sequestration and storage.

3.2 Methods

3.2.1 Study Area Characteristics

The Pockwock watershed, in central Nova Scotia (NS), Canada, is the largest water supply for the province's capital, Halifax Regional Municipality. The watershed has been closely monitored since it was established as a drinking water supply in the 1970s. Following reductions in sulfur and nitrogen emissions, the deposition of acidifying compounds has slowed greatly and surface waters have shown signs of recovery, but this has coincided with an increase in DOC concentrations (Chang and Alexander 1984; Andersson *et al*. 2000; Michalzik *et al*. 2001; Redden *et al*. 2021). Pockwock watershed managers have tracked a significant increase in DOC over time that complicates treatment processes (Anderson *et al*. 2017; Halifax Water 2020). The managing water utility, Halifax Water, is interested in proactively managing the forest to reduce DOC loading while respecting other good management practices in a source water supply.

This research is a continuation of work to characterize and model forest growth and C dynamics in the Pockwock watershed. Using a 1 m digital elevation model (Nova Scotia GeoNova 2012) of the area surrounding Pockwock lake, the lead author used the Arc Hydro extension (Esri 2015) to ArcMap (v 10.5, Esri 2016) to generate a catchment model of the Pockwock watershed (Figure 3.1). This model predicts the area from which overland flow is expected to drain into Pockwock lake. The 5,400 ha watershed includes approximately 4,200 ha of primarily forested land, most of which has been managed for forest products for over 200 years (Hammonds Plains Historical Society 2018). Since its establishment as a water supply in the 1970s, it has been managed with the added objective of protecting water quality (Halifax Water 2009). Today, Pockwock supplies over 200,000 people in the HRM with potable water (Halifax Water 2021); however, increasing DOC concentration in the lake (Anderson *et al*. 2017) is continuing to add costs to treatment, necessitating infrastructure improvements to the water supply treatment plant.

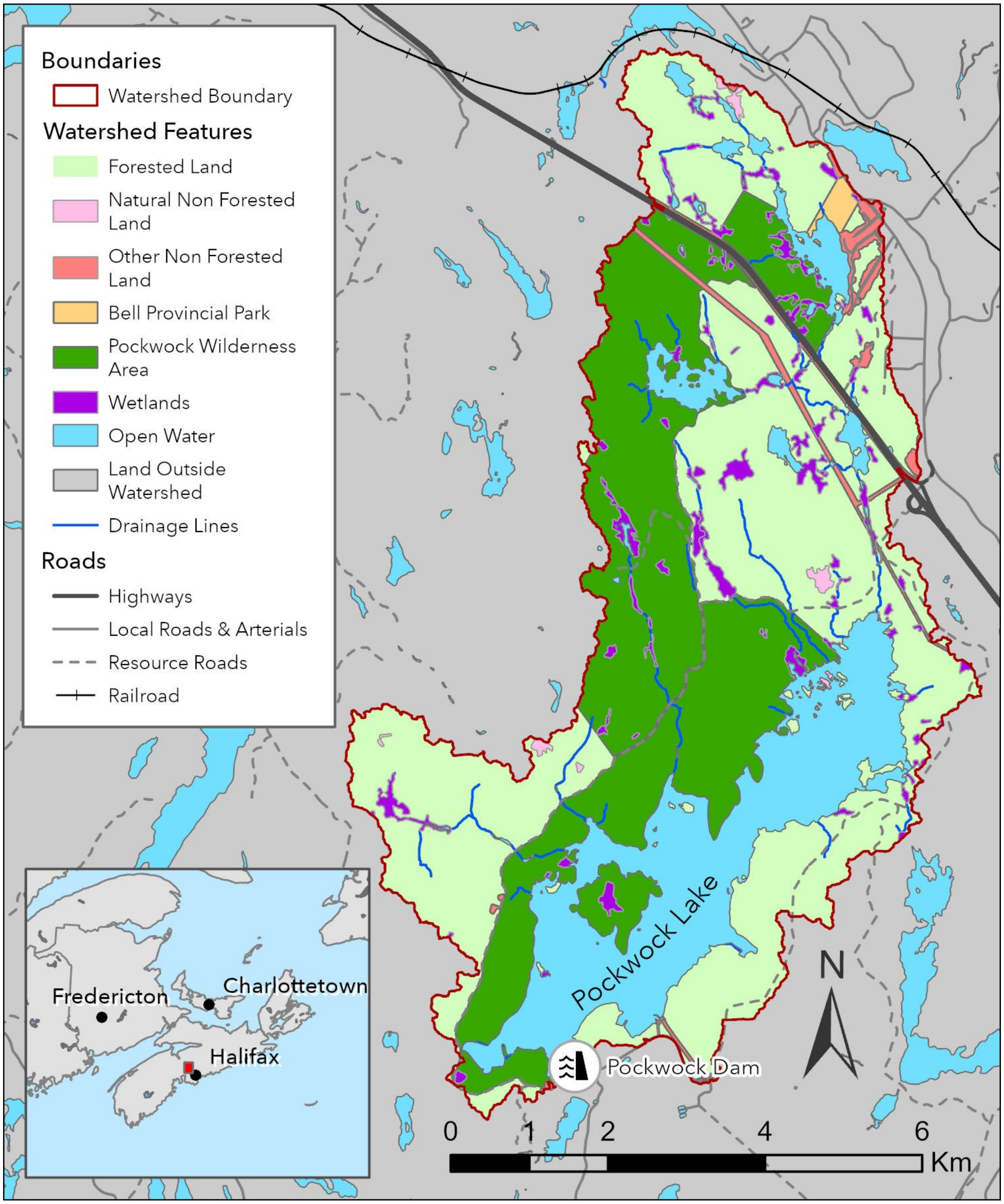

Figure 3.1 The Pockwock watershed (outlined in red) including (inset) the location of the watershed (red box) within Atlantic Canada.

The study area forest is part of the Atlantic Maritime ecozone, a moist, temperate forest that is heavily influenced by the maritime climate (Wiken *et al*. 1996) with a mean annual temperature of 6.6 C and mean annual precipitation of 1,396 mm (Environment and Climate Change Canada 2022). Part of the Acadian forest region, its forests are often conifer-dominated mixedwood stands where growing conditions permit (Neily *et al*.

2017). Dominant tree species include red spruce (*Picea rubens* Sarg.), eastern white pine (*Pinus strobus* L.), balsam fir (*Abies balsamea* (L.) Mill.), red maple (*Acer rubrum* L.), white and yellow birch (*Betula papyrifera* Marsh., *Betula alleghaniensis* Britt.), and eastern hemlock (*Tsuga canadensis* (L.) Carrière).

A comprehensive characterization of the watershed forest, including species composition, land productivity class, estimated ages, and last known disturbances was obtained from the NS Department of Natural Resources and Renewables' (NSDNRR) Crown Lands Forest Model (CLFM) dataset (NSDNRR 2022, Figure 3.2) through a data sharing agreement. Previous work (Foster *et al*., in preparation) adjusted the application of regional growth curves to use at the smaller spatial extent of the Pockwock watershed. Comparing fieldwork data to growth curves developed by NSDNRR found that stands in the Pockwock watershed, at the eastern extreme of its ecoregion, are on average more productive than predicted by regional curves. Yield curves were reassigned in subsequent modelling to better predict merchantable volume (MV) accumulation.

3.2.2 Modelling & Data Analysis

Modelling was divided into three components, each described within this section: C pool initialization, forest management regimes, and disturbance scenario simulation. All data processing and modelling was performed in R Studio (version 2023.06.1 build 524) using the latest version of R at the time (4.3.0) and packages including data.table (Dowle and Srinivasan 2003), tidyverse (Wickham *et al*. 2019), and Rcpp (Eddelbuettel and Francois 2011). Calculations of C accumulation, transformation, and turnover were conducted using an implementation of CBM-CFS3 written by the lead author in R using the processes and calculations from the original model as described in Kurz *et al*. (2009).

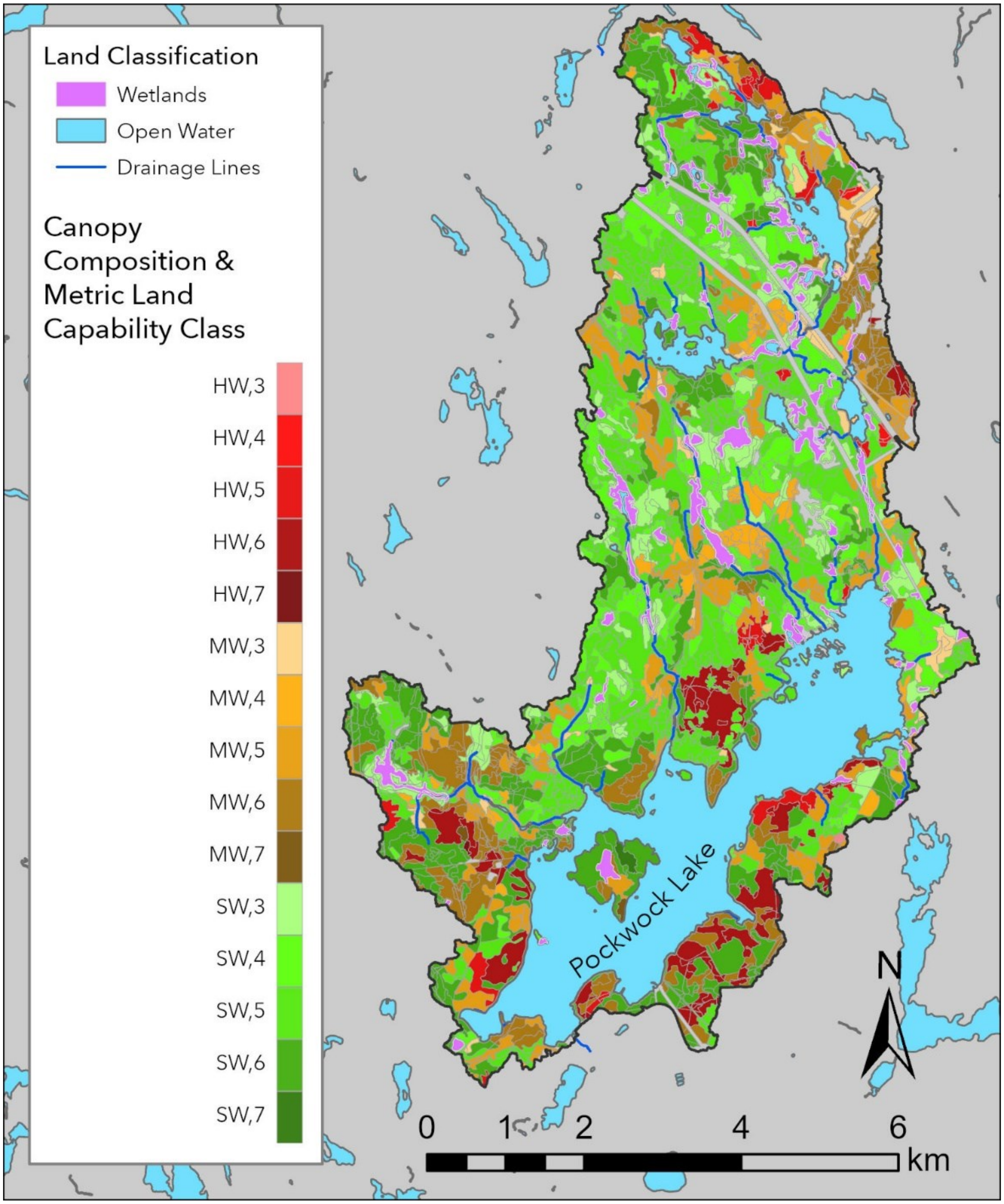

Figure 3.2 Characteristics of forest canopy in the Pockwock watershed. Stands are classified by the relative dominance of tree types, either hardwood (HW), mixed wood (MW), or softwood (SW). Stands are further classified by their metric land capability class, a measure of productivity referring to the accumulation of merchantable volume ($m^3\ ha^{-1}\ yr^{-1}$) over time (3-7). Data: NSDNRR 2022.

CBM-CFS3 is a yield-driven, stand- or landscape-level model that simulates C capture and transformation associated with forest dynamics. The model provides estimates of the movement of C between various DOM pools and compares favourably against similar models for its use in a wide range of circumstances (Kim *et al*. 2015). CBM-CFS3 was developed specifically for the Canadian context and has been successfully applied in NS (Heffner *et al*. 2021), as well as applications elsewhere in North America and on several other continents (Pilli *et al*. 2013; Kim *et al*. 2017; Jevšenak *et al*. 2020; Tang *et al*. 2022).CBM-CFS3 divides DOM into either aboveground (AG) or belowground (BG) pools, and further characterizes them by the rate at which dead materials decay (Table 3.1). It was implemented in R for ease of use with antecedent condition data and flexibility in applying spin-up cycle parameters including type, timing, and combinations of forest disturbances. Biomass was determined from provincial growth and yield curves using stand attributes obtained from the CLFM dataset (NSDNRR 2022).

Table 3.1 CBM-CFS3 dead organic matter pools, adapted from Kurz et al. (2009).

	Aboveground	Belowground
Very fast	Forest floor litter horizon and dead, fine roots (<5 mm)	Dead, fine roots (<5 mm) in mineral soil
Fast	Fine and small woody debris and dead coarse roots (≥5 mm & <75 mm) in forest floor	Dead, coarse roots (≥5 mm) in mineral soil
Slow	Forest floor (F and H horizons)	Humified organic matter in mineral soil
Snag stems & branches	Standing dead stems (of merchantable volume) and branches, including bark	
Medium	Coarse dead woody material	

3.2.2.1 Carbon Pool Initialization

Initialization of C pools establishes soil C conditions at the start of the model run and involved simulating forest growth and mortality cycles under natural conditions (without human intervention) until mineral soil C reached equilibrium between cycles. CBM-CFS3 accomplishes this using a repeating, single disturbance type at consistent intervals, followed by a single, final disturbance, often anthropogenic (Kurz *et al*. 2009). For example: wildfires occur every 150 years until soil carbon is stable, followed by a clearcut. The DOM pool values for the growth period following final disturbance predicts C storage at model initialization for a stand of any given age in that stratum. This approach, and its implementation within CBM-CFS3, is limiting, especially when applied to forests with complex natural or management histories. Sage *et al*. (2019) applied CBM-CFS3 to an historical chronosequence in wet boreal forest in Quebec, Canada, and found that its initialization procedures were limiting and ultimately led to inaccurate estimates of measurable, current-day DOM. Our R-based version of CBM-CFS3 was programed to allow for different numbers and combinations of disturbances to simulate a more complex spin-up routine.

We considered fire and wind to be the most likely, routinely stand-initiating historical disturbance agents, in line with research on regional forest history (Taylor *et al*. 2020). While other agents (especially insects) are substantial components of the region's natural disturbance regime (NDR), the CBM-CFS3 spin-up routine focuses on disturbances that initiate new stands, not produce multi-age stands. Physical transfers associated for each disturbance type were selected from CBM-CFS3 defaults (Kull *et al*. 2011), modified within the R environment to represent extreme scenarios and local conditions (parameters used can be found in Appendix 1: CBM-CFS3 Disturbance Matrices). We modelled the selected two disturbance agents independently and in combination for 20 disturbance cycles to reach a quasi-steady state between cycles. This number of cycles was confirmed to reach this quasi-eqilibrium (as defined in Kurz *et al*. 2009) and is between the 10-30 cycles typically required to reach this state. Following each disturbance, the same stand type was assumed to regrow, an assumption used only for simplicity. For final disturbances, we modelled two clearcuts, 60 years apart, a scenario comparable to historic management patterns in this region. These disturbances were applied to a dominant stand type found in the study area: a productive, softwood-dominated (primarily red spruce) stand.

Annual timesteps of growth for these initialization scenarios (and subsequent stand and forest modelling) were passed through an implementation of the methods from CBM-CFS3 written in Rcpp, a C++ package for R (Eddelbuettel and Francois 2011). This efficiently carried out the calculations described in Kurz *et al*. (2009) within the R environment. C transfers were calculated from living to dead pools, as was gradual turnover between dead pools and losses to the atmosphere.

3.2.2.2 Forest Harvest Regimes

To estimate the relative effects of a range of harvesting practices, we tested a dominant stand type in our study area under five harvest scenarios. We selected five scenarios: (1 & 2) clearcutting at 50- and 100-year intervals; (3) managing for even-aged stands through a two-entry system using a commercial thin after 40 years of growth, followed by a clearcut 20 years later; (4) no harvesting; and (5) creating a multi-aged stand using a high-retention, irregular shelterwood system (McGrath *et al*. 2021). For each case, growth was determined using provincial yield curves developed for stands of specific composition and productivity classes, and under defined management regimes. DOM pools were calculated using our previously described scenario C calculations in our R implementation of CBM-CFS3.

3.2.2.3 Disturbance Scenario Modelling

Anthropogenic and natural disturbances to the forest were simulated in R within the framework established by the original version of CBM-CFS3 (Kurz *et al*. 2009). The design intent for the disturbance scenario model was simplicity and repeatability to provide consistent results that primarily serve to simulate C movement. The model code is available upon reasonable request by contacting the lead author. We separate management into two broad categories: planned harvests and natural disturbance management. Planned harvests are applied only to the portion of the forest that is legally eligible for harvest within a given management scenario. Natural disturbance management is applied on the entire forested landscape and includes measures taken in the aftermath of natural disturbances to mitigate risks to water quality. This distinction is important in our study area because the protected area that comprises 39% of the forested landbase is precluded from planned harvests and proactive disturbance management (e.g. harvesting ahead of a species-specific pest infestation). We tackle each category of management separately.

The model runs on a 5-year timestep and randomly selects eligible stands for both natural and anthropogenic disturbances based on pre-determined criteria. Natural disturbances simulated in the model are fire, wind, and insect, focusing on spruce budworm (*Choristoneura fumiferana* Clem., SBW), and affect an equal proportion of the watershed at each timestep according to the mean annual disturbance rate (MADR) established through regional disturbance literature (MacLean *et al*. 2022).

To be eligible for harvest, a stand must be an area designated for harvest within the context of each model scenario, have reached its maximum mean annual increment (MAI), and not have been disturbed naturally in the same timestep. Designation for harvest is an acknowledgement that many parts of the watershed are legally protected from harvest, either as lands in a Provincial wilderness area, watercourse buffers, or other regulatory restrictions on harvestability. In some scenario runs, this criterion was switched to either extreme, allowing harvests on all or none of the forested watershed. Using maximum MAI as a criterion for harvest eligibility ensures that less-productive forest strands are harvested, despite relatively low MV.

The model is aspatial and does not account for neighbour effects of disturbances, or the logistical or economic constraints associated with harvesting. The assumption of equal area disturbances per timestep differs from known patterns of wildfire spread, insect infestations, and interactions between disturbances. These assumptions, in addition to disregarding logistical constraints of harvest (e.g. reaching selected stands efficiently), were necessary to provide consistency across model runs and allow for comparability between both iterative runs and the scenarios.

The disturbance model was applied in two experiments described in the following sub-sections. The first instance was application to a simplified, hypothetical landscape to determine the effects on C pools from managing natural disturbances alone. The second was watershed-scale model runs that incorporate both natural and human disturbances to study changes to soil C pools across the management scenarios.

3.2.2.4 Natural Disturbance Management

Natural disturbances are an important part of stand dynamics, and efforts are continuously made to better understand their causes, effects, how they are best emulated through harvest systems, and how they will be affected by a changing climate (e.g. MacLean *et al*. 2022). Due to the unique nature of the studied watershed as a source water supply, natural disturbances are proactively mitigated, and their effects are reactively managed to reduce risk to the drinking water supply. The result of these interventions is that the typical NDR and its effects on C dynamics in this region are not expressed in the study area.

Modelling a hypothetical landscape with 4,000 ha of the most common stand type found in the Pockwock watershed, we simulated natural disturbances and their management. The simplified landscape included only one stand type and started with an even spread of stands at all ages. These simplifications were used instead of natural landscape characteristics to control for sources of variability other than the selected management regime, and to ensure that yield curves were assigned correctly following silvicultural treatments. We modelled C dynamics in scenarios including (1) no harvests or mitigation of natural disturbances, (2) management of each natural disturbance agent individually, (3) and disturbance interventions in different combinations. Realistic reactive measures were selected that could be applied in the watershed to minimize C accumulation and, we theorize, reduce C loading in the water supply (Table 3.2). Proactive mitigation measures through forest management were not included in this assessment.

Table 3.2 Summary of natural disturbance agents and how they are applied to the study area, the Pockwock watershed in Nova Scotia, Canada. Columns include stand eligibility requirements, a description of the natural disturbance regime (NDR) and its representation within the model including mean annual disturbance rate (MADR), and how the effects of the disturbance are managed in this modelling context.

Disturbance agent	Eligibility	NDR	Effect	Management intervention	Intervention description
Fire	Stand has a merchantable volume	Complete mortality with 500 yr. MADR	Total mortality within stand	Fire suppression	Fire starts quickly suppressed; annual burn reduced to 1/5,000th forested area (5,000 yr. MADR)
Wind	Stand has a merchantable volume	45% mortality with 322 yr. MADR; blowdown left on site to decay	45% mortality rate within stand	Salvage harvesting	Blowdown from severe wind is salvage harvested in same year (standing trees unaffected)
Insect	Stand is > 40 years old and predominantly softwood	Varying mortality with 250 yr. MADR; mortality left on site to decay	Mortality depends on the proportion of the stand vulnerable to spruce budworm (SBW) – from 10% to 80% in eligible stands	Salvage harvesting	Stems killed by insects are salvage harvested in same year (live trees unaffected)

3.2.2.5 *Watershed Scale Management*

We applied four forest harvest regimes at the watershed level in three natural disturbance management scenarios. Model runs examined 4,000 ha of forested area, representing a range of stand conditions including species composition, age, last disturbance, productivity, and canopy closure (Figure 3.2). These attributes and stand delineations were obtained from provincial forestry records (NSDNRR 2022). Original stands were divided to produce sub-stands of ≤ 1 ha, to provide more flexibility in the designation of areas for disturbances. In total, the modelled areas were distributed across 6,343 stands (Table 3.3). Potential effects of climate change on stand composition were not considered in this modelling.

Table 3.3 Summary of stands modelled in watershed-scale management scenarios. Stands are represented both by the count within each category, and the total area of each category within the modelled landscape.

Stand type indicates relative dominance of trees classified as softwood or hardwood. Protection status determines eligibility for harvest in some management scenarios.

	Count of stands modelled (total area, ha)		
Stand type	**Non-protected areas**	**Protected areas**	***Total***
Softwood	1,849 (1,168)	2,289 (1,411)	*4,138 (2,579)*
Mixed wood	1,122 (685)	628 (382)	*1750 (1,067)*
Hardwood	287 (202)	168 (127)	*455 (329)*
Total	***3,258 (2,055)***	***3,085 (1,920)***	***6343 (3,975)***

Each scenario was run for 40 timesteps, in which each timestep represents five growth years (200 total years), primarily selected to allow for faster model runs. This is dissimilar to CBM-CFS3 which runs on annual timesteps, requiring annualization of data to 1-year timesteps for C calculations. The four harvest regimes include (1) no harvesting, (2 & 3) clearcutting legally harvestable stands at approximately 50- and 100-year intervals, and (4) clearcutting all stands at approximately 50-year intervals. Clearcutting was used as the sole harvest technique to represent the extremes of management – results from comparisons of forest management regimes (3.3.1) demonstrate how carbon dynamics might behave under relatively less-intensive harvesting regimes. The three disturbance scenarios modelled are NDR, NDR with fire suppression, and management of all three disturbances, in what we refer to as the managed disturbance regime (MDR; refer to Table 3.2 for more information on each intervention).

The disturbance model applies natural disturbances first and then harvests. All disturbances, both natural and anthropogenic, are applied randomly to eligible stands until the maximum area per disturbance per timestep is reached. No stand is affected by two disturbances in the same timestep. After the disturbance model is complete, the results are converted to annual timesteps and C transformations and turnover are calculated as above using calculations described by Kurz *et al*. (2009) and implemented in R. Each combination of natural/managed disturbance and harvest regime was run 10 times and the mean values for each timestep were used in analyses.

3.3 Results

When impacted by fire, a substantial loss of C to the atmosphere results in lower soil C retention compared to the wind blowdown regime, in which tree mass is retained on site and decays (Figure 3.3). More time between disturbances results in greater C sequestration in mineral soils. This manifests in the extremes of a fire disturbance every

150 years, and an infrequent wind disturbance, every 300 years. For these scenarios, the mean soil C storage from the initialization values (stand ages 0-150) is 79.9 and 88.8 Mg ha^{-1} respectively. Based on historical disturbance patterns (Taylor *et al*. 2020), we decided on a model spin-up regime that involves stand-replacing blowdown events every 300 years, followed five years later by a fire within the stand. This has a mean soil C storage of 85.5 Mg ha^{-1} from the initialization period and represents a middle estimate of initialization conditions between the other modelled scenarios.

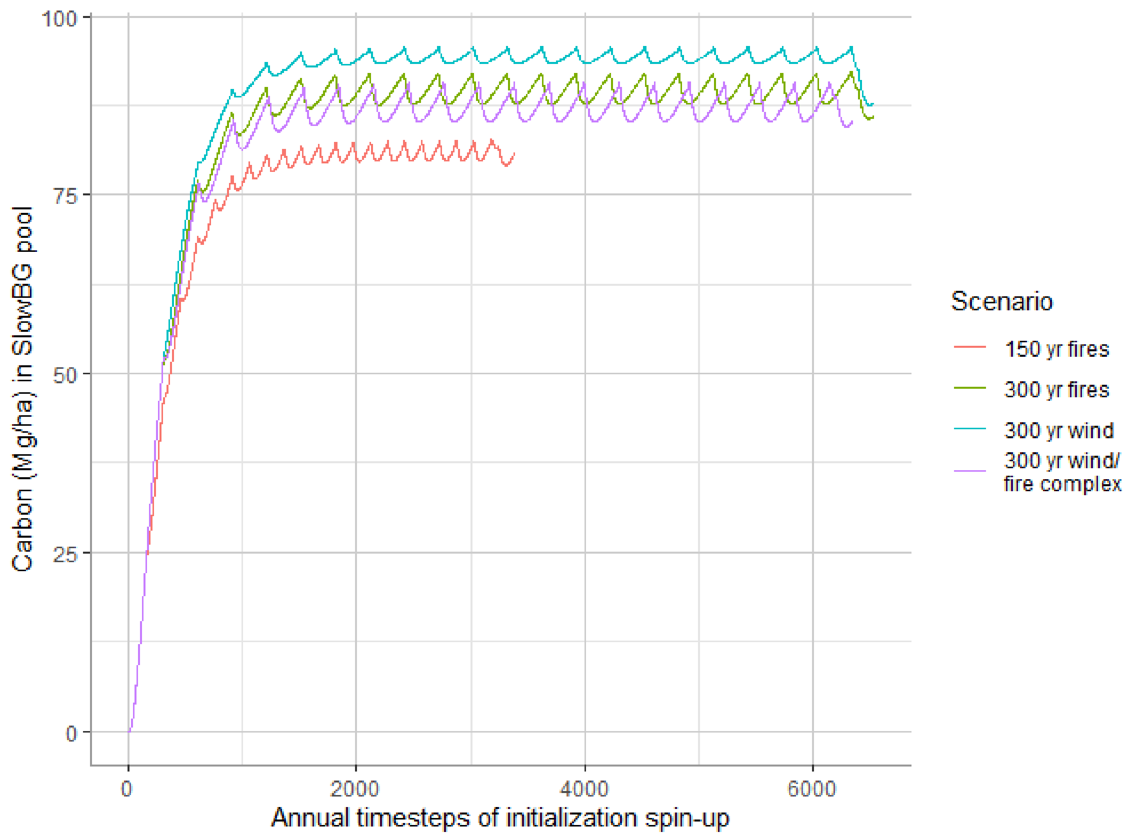

Figure 3.3 Illustration of carbon storage in the slow belowground (BG, mineral soil) pool over several thousand years of CBM-CFS3 model spin-up. The initial period of increases and oscillations finds an equilibrium in carbon storage between disturbance cycles, while the final portion of each line illustrates the effects of final, anthropogenic disturbances.

The use of two final clearcuts before initialization values, in addition to the relatively short period between them, results in lower C storage than a single clearcut in the final disturbance period (Figure 3.4). This pattern of disturbances better approximates the management history of this region, and the ability to model this more complex management regime demonstrates the utility of our implementation of CBM-CFS3 in the R environment.

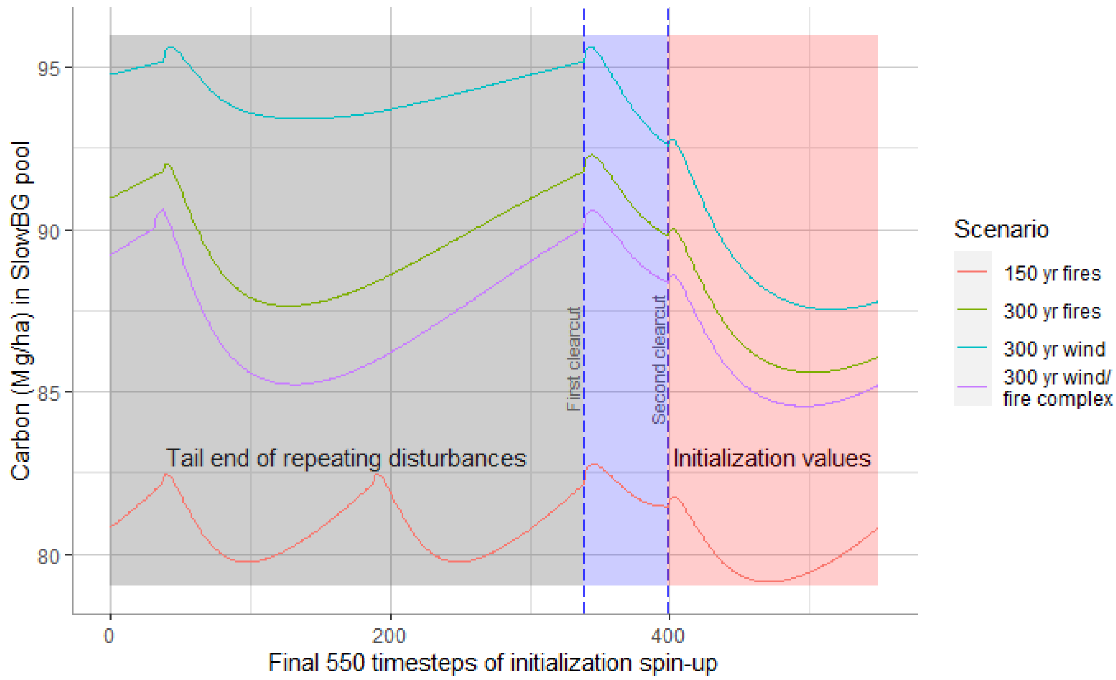

Figure 3.4 Carbon stored in the slow belowground (BG) pool during the final 550 years of stand condition initialization in CBM-CFS3 (Figure 3.3). Each line represents a different initialization scenario including timing and type of disturbance. The blue area represents the 60 years post-first clearcut, and the red area indicates the values used for model run antecedent conditions.

Research on the forest floor in the study area has previously found that stands within the same stratum have a mean forest floor (F and H horizons) C content of 23.2 Mg ha^{-1} (Aksenchuk 2019). This is within the range of estimated values of forest floor C for this stand type from the initialization values (Figure 3.5), which range from 20.3 to 27.2 Mg ha^{-1} across all scenarios. Additionally, measurements of mineral soil C content from unpublished forest soil sampling and ecosystem classification datasets for the study area's region (NSDNRR, unpublished data, retrieved Jun 2023) show that these initialization values are within the expected range of values, though this range is relatively wide.

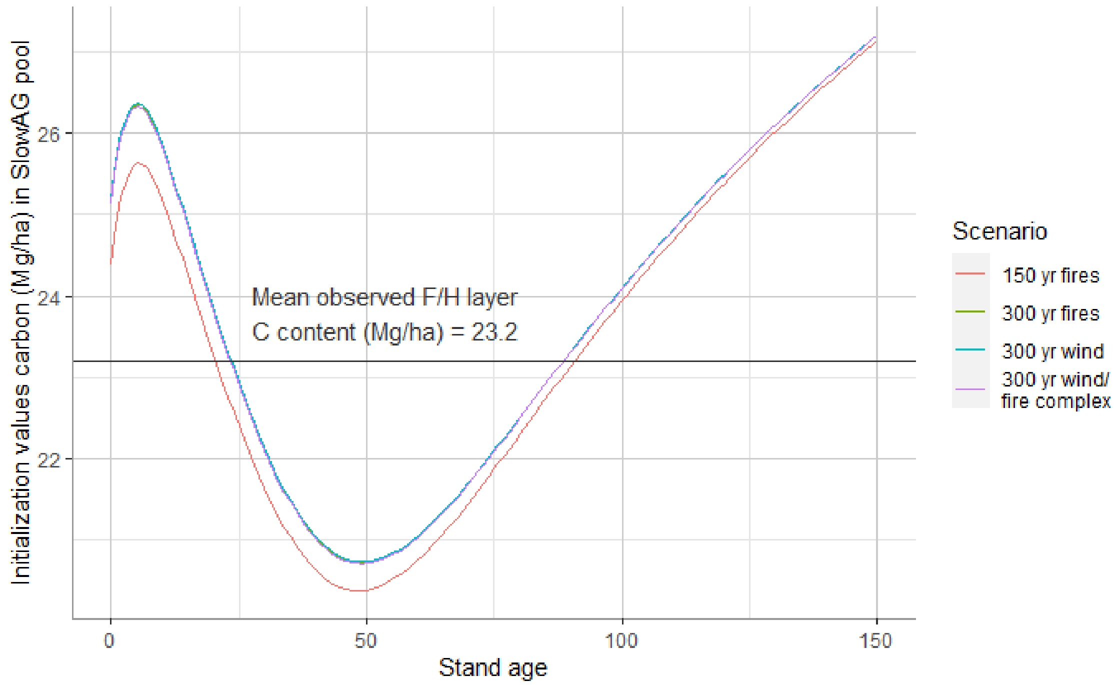

Figure 3.5 Predicted carbon storage slow aboveground (AG) pool in the Pockwock watershed for a stand of varying ages using different initialization parameters (coloured lines), compared to measurements of forest floor carbon from a previous study of the same area (horizontal black line), finding that the average measured value was within the range of expected values from all disturbance regime scenarios.

3.3.1 Forest Harvest Regimes

All scenario results are practically identical for the first 45 years, before silvicultural interventions begin in some scenarios, after which, results vary depending on pool (Figure 3.6). The very fast and fast AG and BG pools (corresponding with litter, fine and small woody debris, and fine roots) fluctuate substantially after harvests. Both slow AG (comprised of the F and H horizons of the forest floor) and slow BG (mineral soil) pools diverge between management regimes following the first interventions, and both pools demonstrate the same pattern of relative C storage under given management scenarios. The least intensive management (no cutting) retains the most C (33.7 and 97.0 Mg ha^{-1} in slow AG and BG respectively), while the most intensive (clearcutting frequently) retains the least (18.7 and 83.5 Mg ha^{-1} in slow AG and BG respectively). Clearcutting less frequently, using a two-entry, even-aged management system, and the multi-aged stand approach through gap irregular shelterwood all offer varying middle grounds between the extremes.

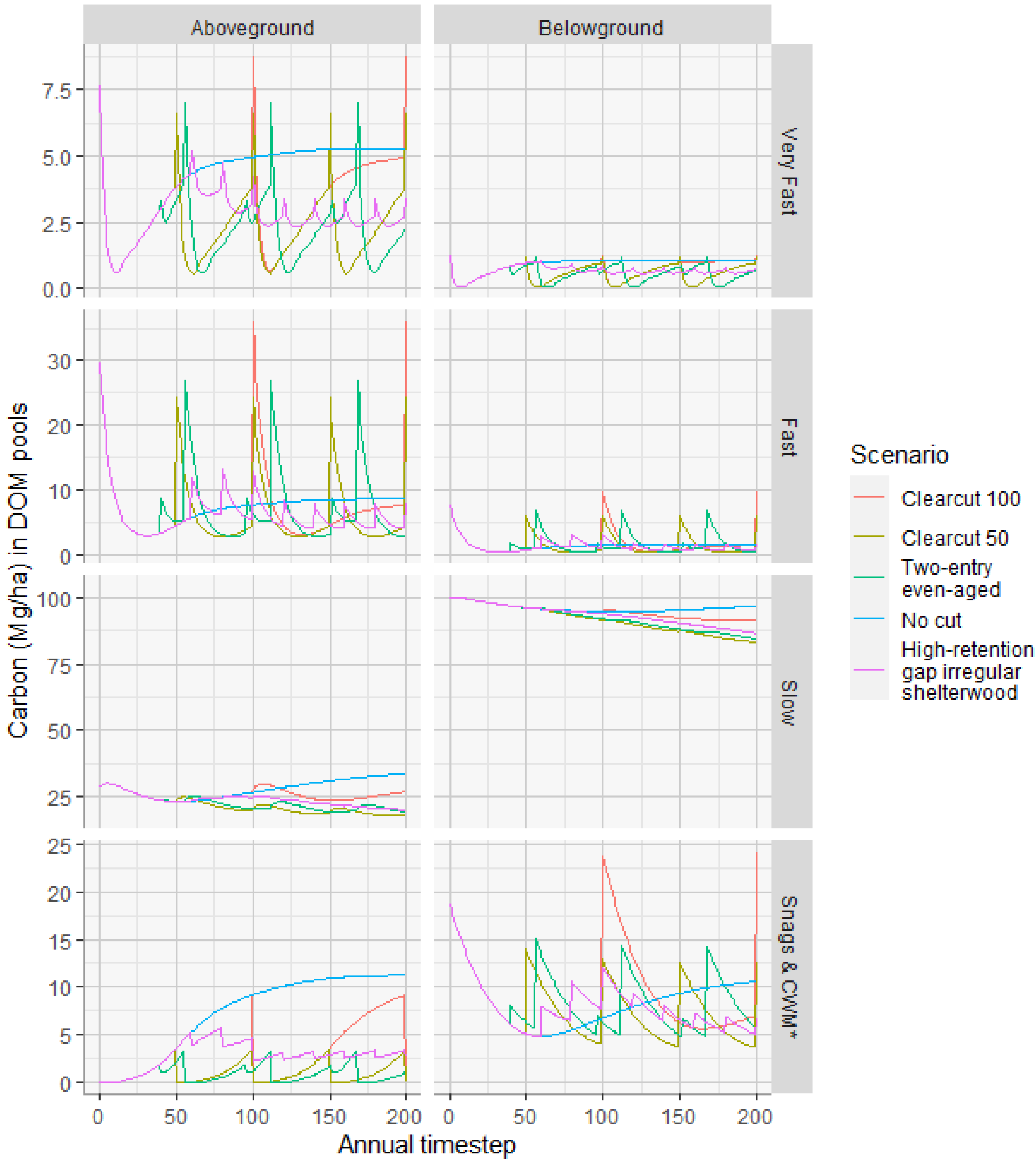

*Figure 3.6 Dead organic matter (DOM) pool carbon contents under differing harvest management scenarios in an idealized landscape. Columns represent aboveground (AG) vs belowground (BG) pools. Rows represent the DOM pools as described in Kurz et al. (2009) *except for the snags and coarse woody material (CWM) row, which combines both stem and branch snags in the AG column, and the medium pool (dead, coarse, woody material) from CBM-CFS3 in the BG column – all of these are in fact AG. Accumulation is identical for the first 40 years, until silvicultural interventions begin in some scenarios.*

The sudden, post-disturbance increase of C in fast and very fast pools dissipates quickly and values trend towards one another between harvests across different management regimes (Figure 3.6). We find that although storage in the non-slow pools is lower than slow AG and slow BG pools, these non-slow pools are responsible for the majority of C lost to the atmosphere (Figure 3.7). Additionally, losses to the atmosphere through decay are substantially different between scenarios. Scenarios involving clearcuts show drastic but short-lived increases in fast and very fast AG and BG pools, but these pools are rapidly drawn down through decay and subsequent C loss to the atmosphere. Despite acute DOM pool peaks following harvests, lower-intensity and non-harvest scenarios lost more C to the atmosphere in the long-run. The no cut scenario saw losses of 124 and 591 Mg ha^{-1} of C from slow and non-slow pools, respectively (Figure 3.7). The most intensive management scenario, clearcuts every 50 years, produced losses of 108 and 383 Mg ha^{-1} of C from slow and non-slow pools, respectively. For subsequent result comparisons, only slow pools will be displayed as they show the most easily comparable results, although non-slow pools will be discussed at greater length.

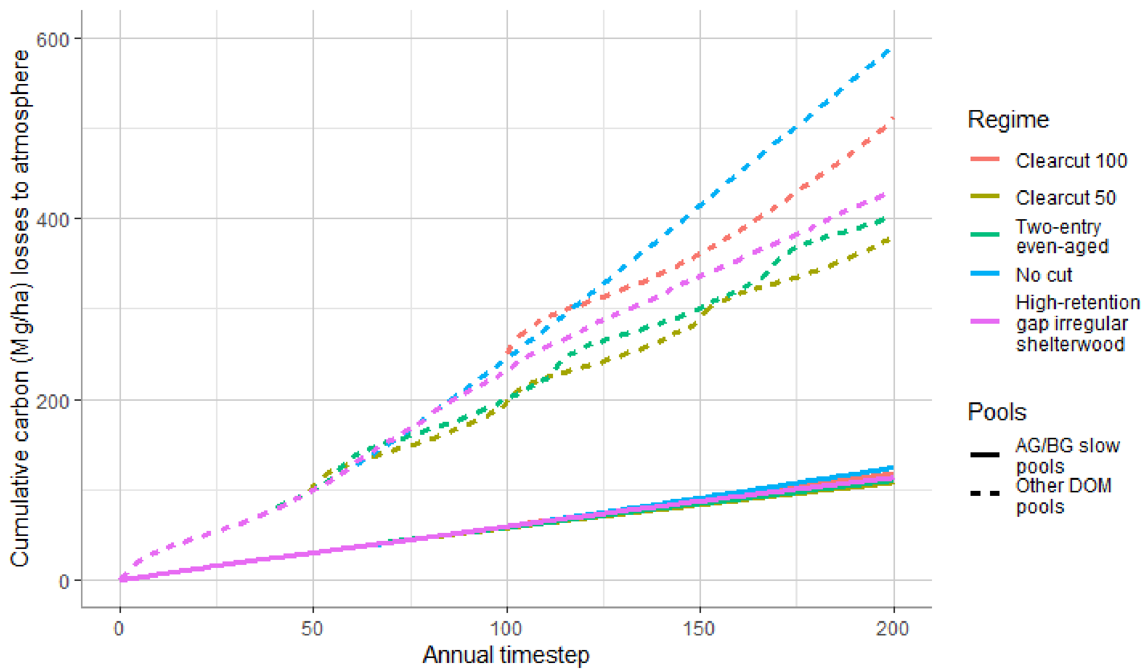

Figure 3.7 Cumulative carbon losses to the atmosphere through decay under different harvest management scenarios in an idealized landscape. Solid lines represent carbon losses from slow aboveground (AG, forest floor) and belowground (BG, mineral soil) pools only, while dotted lines represent losses from all other dead organic matter (DOM) pools described in Kurz et al. (2009).

3.3.2 Natural Disturbance Management

Model runs of an unmitigated NDR yielded mid-range DOM pool values compared to other scenarios, with 31.6 and 95.4 Mg ha^{-1} of C in the slow AG and BG pools after 200 years, respectively (Figure 3.8). NDR mitigation measures have varying effects on C sequestration. Salvage logging after wind or insect disturbances decreases C in both AG and BG slow pools as C from the stem (MV) is removed from the landscape after mortality. When applied together, their effect is additive and produced the lowest C storage in slow AG and BG pools by the end of the model run, 30.2 and 94.6 Mg ha^{-1} respectively. Fire is a powerful agent of C loss from the landscape, exporting C from AG pools to the atmosphere. Fire suppression, therefore, caused a net increase in C storage over time compared to the NDR scenario and resulted in the highest values for slow AG and BG pools and the end of the model run, 33.7 and 97.3 Mg ha^{-1} respectively.

C storage in the MDR, in which all interventions are enacted, is midway between the NDR and fire-suppression regime (Figure 3.8). This represents the most likely scenario as practiced within the watershed today as fire is actively suppressed and significant blowdowns and standing deadwood from widespread insect infestations may be salvage logged.

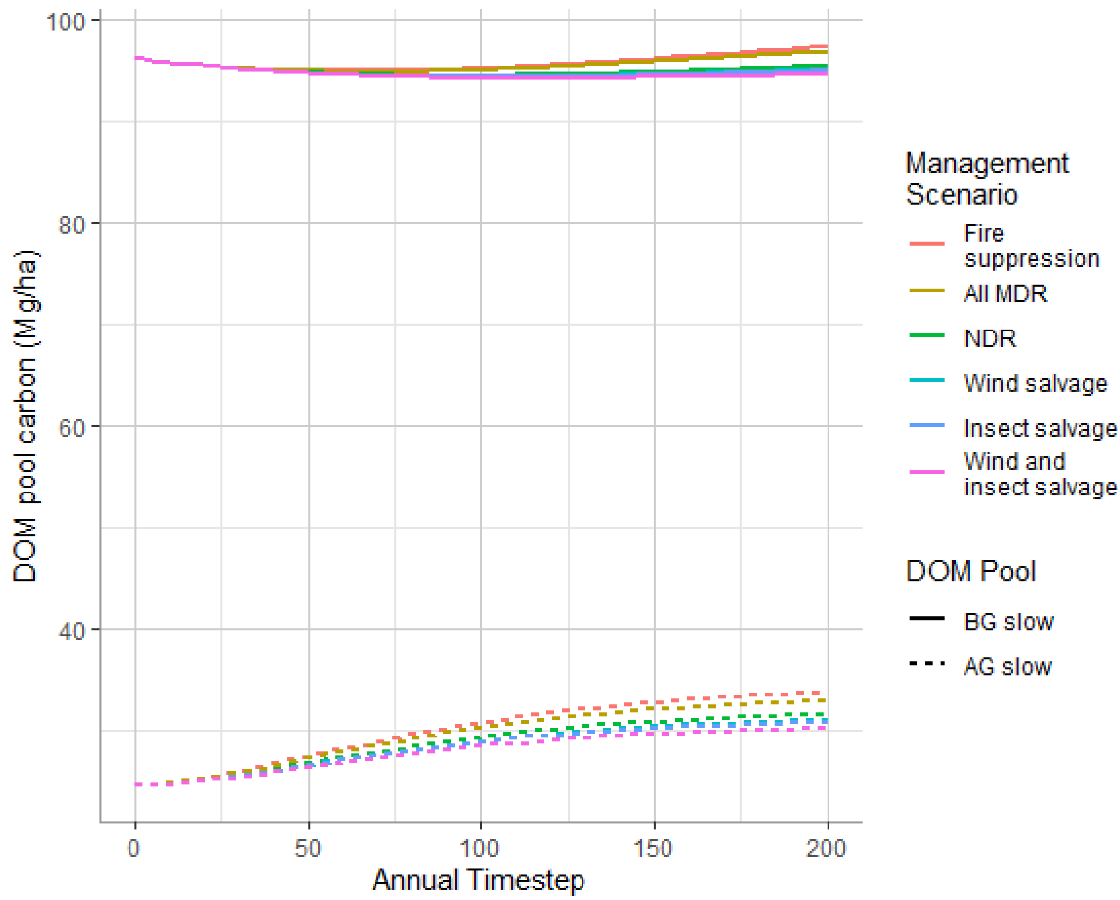

Figure 3.8 Carbon (C) storage in slow aboveground (AG, forest floor) and belowground (BG, mineral soil) dead organic matter (DOM) pools under different natural disturbance regime (NDR) scenarios and their management, including a scenario involving all interventions, the managed disturbance regime (MDR).

3.3.3 Watershed Scale Management

Watershed scale modelling demonstrates similar trends in C storage as observed in 3.3.1 Forest Harvest Regimes. The no harvest scenario produced the greatest C storage across the watershed while frequent clearcuts throughout the entire watershed resulted in the lowest storage (Figure 3.9). The effect of NDR management had an impact on stored C at the watershed scale consistent with testing on stands in 3.3.2 Natural Disturbance Management, however, the effect of NDR interventions was lower than that of changes to harvest regime.

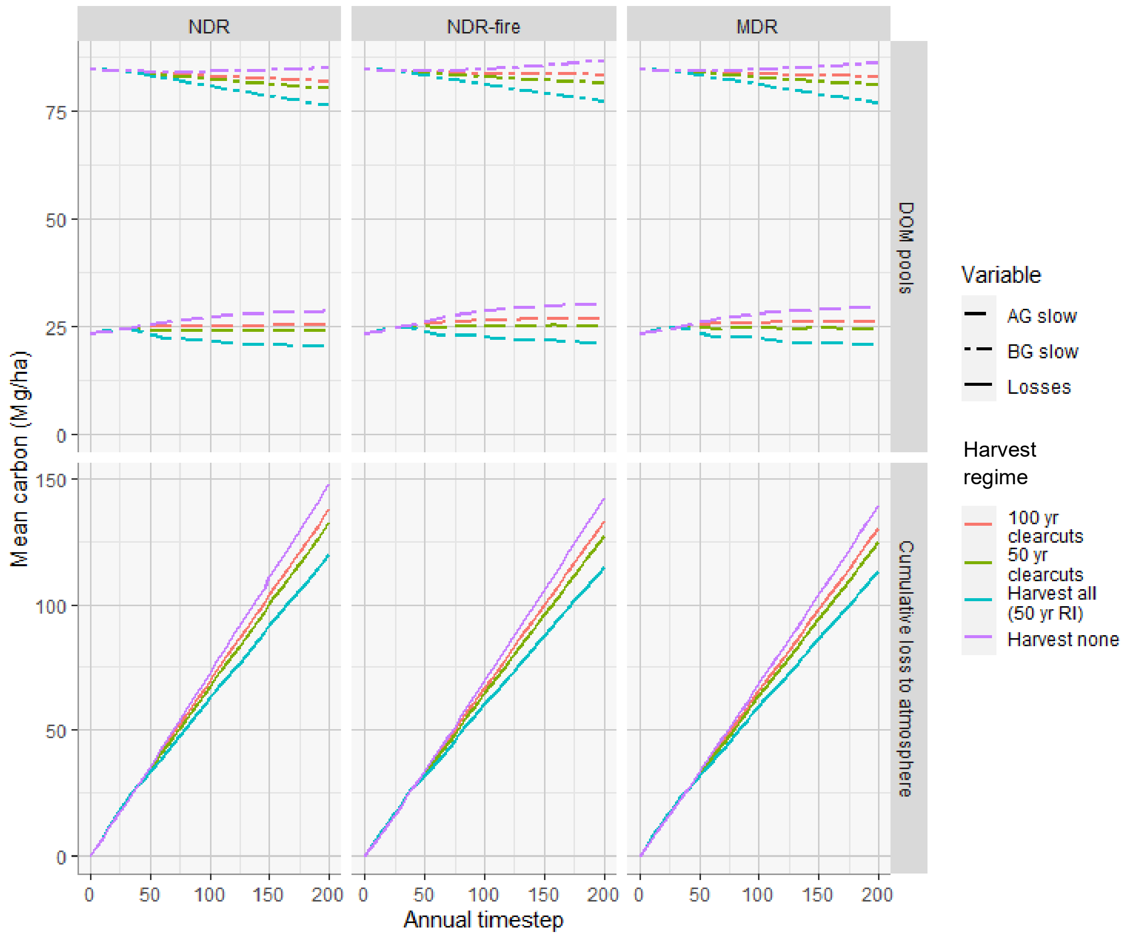

Figure 3.9 Illustration of carbon dynamics during watershed scale management scenarios using four harvest scenarios (indicated by line colour) and three natural disturbance regime (NDR) management scenarios (within each column), including a fully managed disturbance regime (MDR). The top row of graphs demonstrates both slow aboveground (AG, forest floor) and belowground (BG, mineral soil) dead organic matter (DOM) pools in relation to one another, while the bottom row indicates cumulative carbon losses to the atmosphere from all AG and BG pools for each scenario. Harvest scenarios operate on one of two return intervals (RI), 50 or 100 years.

The effect of varying management scenarios causes a relatively small difference in slow pool C storage per unit area, however, total change in stored C at the watershed scale of 4,000 ha is not insubstantial. In the MDR scenario, the difference in stored mineral soil C between the 50 year clearcut and no harvesting regimes is approximately 2.5 Mg C ha^{-1} (Figure 3.10), or 11.5 Gg over the whole watershed. Recalling the highly dynamic nature of these pools, and that sustained pool growth involves both greater inputs and outputs, and may have consequences on hydrologic C export and resulting water treatability. These results pertain only to C dynamics within the watershed, and do not account for C export via removal of harvested MV, thus it reflects the carbon dynamics of the forest ecosystems but not a full carbon balance of the watershed.

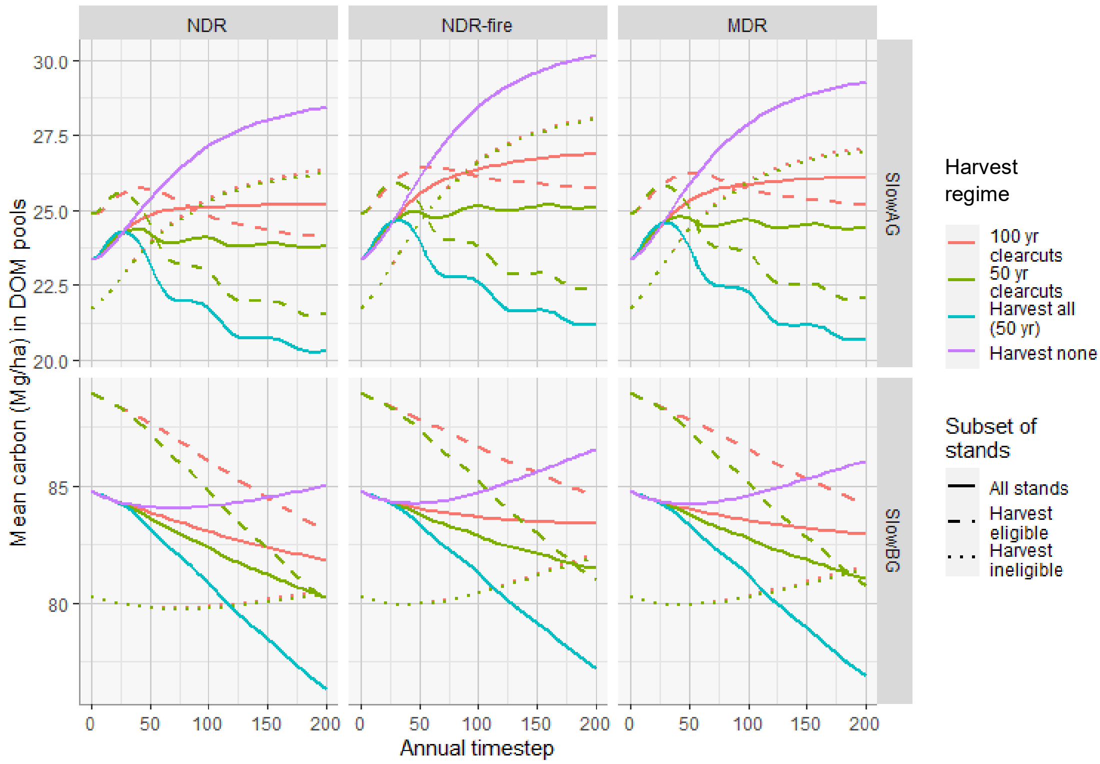

Figure 3.10 Focus on slow aboveground (AG, forest floor) and belowground (BG, mineral soil) dead organic matter (DOM) pools (within each row) under four harvest regimes (indicated by line colour) and three natural disturbance regime (NDR) management scenarios (within each column), including a fully managed disturbance regime (MDR).

3.4 Discussion

3.4.1 Results of Slow vs Non-Slow Pools

Results from watershed scale management model scenarios show that both planned harvests and management interventions of natural disturbances have relatively small, though consistent, impacts on mineral soil and forest floor slow C pools (Figure 3.9). Our results are consistent with the design of the original CBM, that the slow pool is "effectively steady state" with relatively small changes following infrequent disturbances (Kurz *et al*. 1992).

Research on Vancouver Island, British Columbia, found that the "inherent stability of the soil C pools" minimized the influence of forest management activities on C losses (Smiley and Trofymow 2017). While frequent disturbances have the potential to gradually impact soil C storage, as observed in our results, this process is slow and leads to relatively small changes in storage over timescales relevant to management planning. Instead of focusing solely on C held in a relatively stable pool, future research into the application of CBM-CFS3 for estimating hydrologic C export should examine the role of non-slow pools more closely, and our results provide suggestions for this research.

Litter and dead fine roots, both constituents of the very fast AG pool, represent a substantial and continual input of C to ground-level DOM pools (Neff and Asner 2001). Litter C is solubilized readily by water (Guggenberger and Zech 1993) and may play a priming role in mobilizing C for export through interactions with microbial communities (Zhang *et al*. 2020). Annual root mortality (Edwards and Harris 1977) and bulk additions from tree or stand mortality events result in regular additions to AG and BG very fast and fast pools that are decayed relatively quickly, become labile, and are often solubilized in soil water. These non-slow pools are, collectively, responsible for a greater volume of C lost to respiration than slow pools in our model runs (Figure 3.7). CBM-CFS3 assumes these losses are to the atmosphere, but the highly soluble nature of C in litter, plus high precipitation characteristic of the region would likely generate additional C losses through quickly flowing lateral or surface runoff in storm events. AG pools in particular, due to the relative stability of BG inputs to soil C comparatively (Sokol and Bradford 2019), should be more closely examined in subsequent research to assess their potential losses to hydrologic export.

Paired with management scenario modelling such as we presented here, investigation may help determine whether harvests and disturbance management are able to affect stream DOC to a greater degree than is suggested by the results of Smiley and Trofymow (2017). Aitkenhead *et al*. (1999) found that especially in smaller watersheds (<5 km^2), soil carbon content is a good predictor of stream DOC concentrations, suggesting that increases to this pool will result in increases to DOC export. Research in Sweden supports this hypothesis, finding that afforestation was a primary explanatory variable linked to increases in stream water colour and DOC (Škerlep *et al*. 2020).

3.4.2 Implications of Forest Management

We tested several practices that are applied in source water supply watersheds including fire suppression, avoiding extensive harvesting, and retaining dead wood. Each in their own way, these management decisions support traditional metrics of good water quality, ease of treatability, or environmental integrity. Fires pose numerous risks to drinking water source water supplies including increased turbidity, increased nutrient and metal runoff, and corresponding risks of contamination from firefighting activities

(Emelko *et al*. 2011; Martin 2016; Nunes *et al*. 2018; Emmerton *et al*. 2020), and are therefore proactively mitigated and reactively suppressed. Intensive harvests, especially on slopes, present risks of increased sedimentation and nutrient runoff that challenge water treatment (Corbett *et al*. 1978; Swank *et al*. 2001; Nieminen 2003) and are opposed on many aesthetic and ecological grounds, and therefore may be avoided in source water supplies. Salvage harvesting after wind and insect disturbances removes snag and coarse downed woody material stock that are important with respect to forest biodiversity and long-term nutrient supplies. Therefore, on ecological and forest sustainability grounds, salvage harvesting is often not practiced.

Our model harvest and disturbance management scenarios suggest, however, that these practices may not be optimal for lowering hydrologic C export. Each serves to increase C storage in DOM pools, including mineral soil where it can be stored over long periods. This is generally a desirable outcome from a climate change mitigation perspective. However, when managing a source water supply with already elevated and continually increasing DOC, a new approach may be required to balance traditional water quality parameters with reducing DOC loading.

3.4.3 Custom CBM-CFS3 Implementation

Our implementation of CBM-CFS3 in R added the flexibility of a spin-up routine that is more complex than single repeating disturbances followed by a single final disturbance. This added complexity contributed to accurately establishing antecedent conditions for model runs, and partially addresses the points raised by Sage *et al*. (2019) who found CBM-CFS3's spin-up procedure to be limiting. Our approach does not model gap dynamics that are the dominant disturbance regime in NS forests (MacLean *et al*. 2022), but nonetheless represents a more complex series of major, stand-replacing events that help estimate C accumulation and antecedent conditions for model runs. This demonstrates an important area for potential expansion of CBM-CFS3 to better represent forest dynamics across not only the Canadian landscape, but globally as the model is applied on many continents (e.g. Pilli *et al*. 2013; Kim *et al*. 2017; Jevšenak *et al*. 2020; Tang *et al*. 2022).

3.4.4 Implications for Drinking Water Supply

Among water utilities in Canada, Halifax Water is in a relatively unique position in that the majority of the watershed's 4,000 ha of forested land is owned by the province and is actively managed to improve water quality (Halifax Water 2021). Expropriated from private forest concerns in the 1970s, the Pockwock watershed has since been managed largely according to direction by Halifax Water. Management practices have changed over time in accordance with provincial regulations on forest practices, including a move away from clearcut harvests to include, primarily, partial harvest systems. Watershed management also includes natural disturbance management, both proactively and reactively, to minimize the effects of disturbances on the forest, and therefore protect the quality of water that it produces (B. Geddes, watershed manager, personal communication, 2022).

The forest is managed to minimize the impacts on water by limiting the occurrence and severity of natural disturbances including fire, pests, and wind. Wind management is particularly important in this area as the region is subject to intense storms in all seasons (Taylor *et al*. 2020). Mitigating wind risk includes applying harvests according to wind risk assessments to reduce post-harvest windthrow, and salvage-harvesting downed, merchantable stems after such events, while other material is laid on the ground to speed natural decay and reduce fire risk. The impacts of insects are mitigated by proactively removing species in the face of significant disturbances, such as the periodic mass mortality events caused by the native SBW that defoliate spruce-fir stands (MacLean 2019). Like wind management, mortality from insect disturbances, especially where concentrated, can be salvage-harvested, or placed on the ground to avoid forest fire fuel accumulation. Fire management includes the previously described methods to limit fuel accumulation, preventing fire starts by limiting human activities that are frequently associated with fires, and by rapidly responding to and suppressing any fire starts that may occur naturally or otherwise.

Our results demonstrate that these natural disturbance mitigation measures, particularly salvage harvesting, are likely serving to decrease the accumulation of C in DOM pools and may potentially reduce export of DOC to aquatic systems. On the other hand, the results suggest that fire suppression is leading to increased C storage in DOM pools and possibly subsequent DOC export. These competing influences of C storage are driven by the need to serve traditional metrics of water treatability with emerging priorities, especially increases in DOC. Similarly, this paper examines the impacts of management interventions on relative DOM accumulation but does not make any claims as to the effects of varying management techniques on other water quality parameters. Further study is required to better understand the balance between these two priorities and the magnitude of impacts that management decisions can have on each.

Public ownership of most of the watershed grants Halifax Water an uncommon level of control over the forest's management, however, some key limitations challenge their ability to proactively manage for water quality. A large portion of the watershed (1,600 ha or ~39% of the total forested area) is designated as provincial wilderness area, precluding planned harvest and silviculture activities. With Ministerial approval, the utility may direct salvage operations in this protected area following significant natural disturbances that would threaten the water supply (especially fuel management following a wind event). This designation prevents proactive management of any of the previously described disturbances, however, as well as forest age class or species distribution management. In the remaining 2,000 ha of forest in which harvests are permitted, operations must be in accordance with evolving provincial regulations on permitted harvest practices, especially a recent push to drastically reduce or wholly eliminate clearcutting on public lands (Lahey 2018).

The primary goal of forest management interventions in the Pockwock watershed is to ensure the sustainable provision of easily treatable potable water. Silvicultural practices are applied not to maximize MV or meet conservation goals, but rather to minimize disturbances to the water supply. Collected in and filtered by the forest, water is the product of interest, and the forest is managed to protect it. This management regime stands in contrast to many forests where the MV is the product of interest, the wildlife habitats provided by the forest are prioritized, or perhaps the carbon stored in living and dead pools is of primary importance. Thus, in the interest of maintaining water treatability, a solution that singly maximizes MV growth, prioritizes biodiversity metrics, or focuses on carbon accumulation will not be sufficient on its own. A balanced approach that maintains water quality is required in this unique setting, understanding the wide range of potential threats that may compromise the water quality.

3.5 Conclusion

We modelled various forest management scenarios using CBM-CFS3 and found that forest harvests and natural disturbance management substantially affect C accumulation in the forest floor and soil. While changes in C storage to the largest pool, i.e. the mineral soil, are gradual, this is not unexpected given the design of the model and stability of mineral soil C. Rapid fluctuations of C in other pools, including forest litter and decaying roots, reveal that they may be a more useful future focus area in relation to managing a forest to influence DOC loading on a source water supply.

Common forest management practices in water-supply watersheds often lead to increases in C pools. Interventions such as suppressing fires, avoiding extensive harvests, and leaving natural mortality to decay on the landscape result in DOM accumulation that may be exported hydrologically. Future research should examine the nature of these C pools more closely to better understand how to strike a balance between managing for traditional water quality parameters and mitigating DOC loading. Specifically, tying the results of this research to existing understandings of the C lability in such pools would be useful to better understand how specific forest management practices contribute to the hydrologic C export. Furthermore, hydrologic modelling tied to carbon management scenarios of settings such as these may reveal more about the potential impact of forest management on water treatability.

In an era of climate change and intensifying land uses, water managers face increasing complications in meeting society’s expectations for potable water. How lands are managed are critical for drinking water supplies coming from surface water sources, thus assumptions about the right way to manage forests may require revisiting when it comes to optimal solutions for sustainably satisfying the need for potable water.

Chapter 3 References

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4 Timber Management Reduces Long-Term DOC Export

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Abstract

Dissolved organic carbon (DOC) concentrations are increasing in many parts of eastern North America, presenting challenges to water treatment processes. We sought to determine if forest timber management can affect DOC exports in the long term by removing carbon (C) from the system through timber harvesting, and the relative magnitude of these effects versus those expected due to climate change. The Pockwock watershed in eastern Canada provides potable water from a primarily forested surface reservoir and is minimally impacted by anthropogenic activities aside from forest management. An integrated modelling framework was produced to simulate forest growth and management, hydrologic response under different future climate scenarios, and corollary DOC export using a variety of field data and other sources. C pool sizes and respired losses were inversely related to management intensity, indicating that harvest removals reduced C available for hydrologic export. Stream monitoring found no short-term, acute DOC response to harvests, an important consideration for total DOC loading. Using calibrated hydrologic models and a range of climate scenarios, the relationship with management intensity was stronger than the effects of precipitation and temperature regime changes in the long term. These findings support the use of timber harvesting as a tool to reduce DOC loading from forested areas to source waters over the long term, although there are several caveats to this finding. Unknowns associated with interactions between climate and the environment, other impacts from harvesting, and potential changes in the role of wetlands may all affect DOC export dynamics. While a cautious approach is required, harvested timber removals reduce overall C availability for hydrologic export and should be considered an important tool for managing water supplies sustainably.

4.1 Introduction

Forest carbon (C) cycles are a subject of intense research and discussion, usually centred around the notion of promoting C sequestration and contributing to climate-change mitigation (e.g. Jevšenak *et al*. 2020; Mäkipää *et al*. 2023). To this end, an increasingly recognized goal of forest management is to sequester C in living biomass (trees), in timber products, especially long-lived products like lumber, and maximize storage in mineral soils where C may remain for centuries (Smyth *et al*. 2014). The steady accumulation of C in forest biomass, punctuated by losses caused by anthropogenic or natural causes, belies substantial fluxes of C in and out of forests on a continuous basis (Kurz *et al*. 2009).

Biomass decay processes in forests are facilitated by macro- and microorganisms and result in both the formation of recalcitrant compounds that are resistant to further decomposition or export and massive releases of C back to the atmosphere as CO_2 and other carboniferous gasses (Harmon *et al*. 2011; Prescott 2010). For a variety of reasons, especially the importance of this C release to the C balance, this is a carefully studied area of forest processes. However, it is not the only major mechanism of C export from forest landscapes. Labile C in all layers of the forest floor and mineral soil can be dissolved by water and transported by hydrologic processes either vertically down through the soil column, or laterally, to surface water systems (Wu *et al*. 2014). Dissolved organic carbon (DOC) is a natural and essential constituent in water, and this mechanism of C export is recognized as an important part in the overall forest C balance (Chapin *et al*. 2006).

DOC contributes to the overall mass transfer from terrestrial to aquatic systems (Hope *et al*. 1994) and plays several important roles along the way including terrestrial to aquatic mass transfer (Hope *et al*. 1994), transporting minerals and metals (Lawlor and Tipping 2003), and shading aquatic fauna from UV rays (Schindler 1971). Natural ranges of stream DOC concentrations vary greatly across ecosystem types and are largely influenced by climate, wetland presence, and forest composition (Li *et al*. 2015; Wallin *et al*. 2015). In Nova Scotia, on Canada's Atlantic coast, DOC concentrations are among the highest in North America (Clair *et al*. 1994; Hope *et al*. 1994). Throughout much of the 20th century, however, soil biological processes were suppressed by acidifying deposition, resulting in lower DOC export (Evans *et al*. 2012; Hruška *et al*. 2014). Subsequent reductions in acidifying deposition due to international agreements between

Canada and the United States has resulted in recent DOC increases in surface waters in the region (Anderson *et al*. 2017). The legacy of acidifying deposition has altered forest soils, including substantial Ca^{2+} leaching that may continue to promote DOC exports into the future (Lawrence and Roy 2021). While deposition regime changes have altered DOC export, many researchers are attempting to better understand the influences that a changing climate and forest management will also exert on DOC export regimes.

DOC export is controlled by several variables. The timing and intensity of precipitation in combination with air temperature, which affects both microbial activity and precipitation type (i.e. liquid or solid), are key controls on the production and export of DOC (Wen *et al*. 2020). DOC export from some landscapes is more closely correlated with temperature, while others more so changes in flow (Winterdahl *et al*. 2016). Overall, researchers have predicted that due to a positive correlation between mean annual temperature (MAT) and DOC export, increasing MAT will result in greater DOC export (Laudon *et al*. 2012). Additionally, whereas DOC export in some landscapes is most significant during peak flow events, changing timing and intensity of precipitation and peak flow events also contribute to greater DOC export (Wilson *et al*. 2013). Understanding these relationships and attempting to predict DOC export under future climate scenarios requires modelling that incorporates landscape and climate variables.

A variety of approaches to modelling DOC export have evolved over time with increasing environmental data availability, understanding of the relationships between environmental variables and DOC, and computing power. Regression models (e.g. Creed *et al*. 2008) have been used in an attempt to relate DOC concentration and total export to hydrology including discharge and physical hydrological factors. Empirical modelling approaches attempt to explain DOC export variability as a function of different environmental variables such as soil factors (Boyer *et al*. 1996), C additions to the forest floor (Currie and Aber 1997), and combinations of the above in addition to interconnectedness of systems and variables (Michalzik *et al*. 2003; Worrall and Burt 2005; Xu *et al*. 2012). The Integrated Catchments Model for Carbon (INCA-C, Futter *et al*. 2007) is a watershed-scale process model that simulates soil and in-stream C processes using a wide range of parameters. Most recently, machine learning has been harnessed to uncover correlations between DOC export databases and a variety of environmental factors to better understand the causes of variation in DOC production and export (Toming *et al*. 2020). However, a key complication in modelling forested landscapes, and one that is not represented in current modeling approaches, is the dynamic nature of forest growth and mortality, including anthropogenic influences.

The Pockwock watershed, on the edge of the Halifax Regional Municipality, Nova Scotia, serves over 200,000 people with water and is managed by Halifax Water, the region's water utility. The headwater lake sees relatively few anthropogenic impacts from development or other human activity except for forest management, but lake DOC has increased steadily for over 20 years (Anderson *et al*. 2017). DOC is removed from drinking water early in the treatment process, and is facilitated by the addition of aluminum sulphate, a flocculant that causes C to come out of solution for physical filtration (Matilainen *et al*. 2010). Increasing DOC has required substantial investments in water treatment infrastructure to date, and DOC concentrations show no signs of levelling.

This research builds on earlier work in this watershed seeking to address this ongoing trend of DOC increases. Recent work in forest C modelling found a clear relationship between forest timber management regime and the accumulation of C in the forest (Foster *et al*. 2024). The intensity of forest timber management was found to be negatively correlated with the accumulation of C in dead organic matter (DOM) pools, such that an intensively managed forest accumulates less C in mineral soils than one that experiences no management interventions at all. Further analysis found that the watershed's DOC export is transport limited, indicating that hydrologic flow volume should positively correlate with DOC export (Langelaan 2022). This research will seek to determine if, when coupled, these relationships mean that the intensity of forest timber management is also inversely correlated with DOC concentrations. Specifically, we seek to determine if, under a range of climate scenarios, differing forest timber management regimes can elicit appreciable changes in DOC export over practicable timescales, and therefore be used to mitigate future DOC loading in the water supply. If true, this would provide watershed managers at Pockwock, and other water utilities, with a better understanding of the influence of forest management activities on water treatability from a DOC standpoint.

Based on past research in the study watershed, we hypothesize that the amount of C exported hydrologically is inversely related to the intensity of forest timber management activities. Additionally, whereas climate change causes generally warmer conditions with greater precipitation we predict that increases in decay rates and soil water throughflow would contribute to further increases in DOC production and export. To address these questions, we developed and calibrated an integrated modeling framework to predict annual DOC export as a function of forest timber management and climate, and forced the model with a suite of climate change projections and hypothetical forest management regimes.

4.2 Methods

4.2.1 Study Area Overview

The Pockwock watershed is in Nova Scotia, on Canada's east coast (Figure 4.1). Subject to a maritime climate, the study area receives an average annual precipitation of 1,396 mm and has a mean annual temperature (MAT) of 6.6 C (Environment and Climate Change Canada 2024). Climate patterns include average temperature lows and highs of -8.8 and 24.7 C in January and July, respectively, and the highest precipitation in November, December, and January (descending order) with drier summer months (June, July, and August) (Environment and Climate Change Canada 2024). This climate supports a temperate forest composed predominantly of conifer-dominated mixedwood stands on zonal sites (Neily *et al*. 2017). The watershed's soils are primarily medium-coarse Podzols derived from quartzite/slate tills (Halifax series) and granite/granodiorite tills (Gibraltar series) (MacDougall *et al*. 1963). Owing to the moist climate and coastal winds, wind and insect/disease pests are the most common natural disturbance agents of forests (Taylor *et al*. 2020) and not fire, as in much of the rest of North America.

Pockwock Lake is a headwater lake fed primarily by six streams draining tributaries from a primarily forested land area of approximately 4,200 ha (Figure 4.2). Through the J.D. Kline treatment plant, Halifax Water supplied over 33 million m^3 of potable water from Pockwock Lake in 2022-2023 (Halifax Water 2023). Pockwock Lake has experienced increasing DOC over almost five decades (Halifax Water 2020), a common trend in this region (Anderson *et al*. 2017).

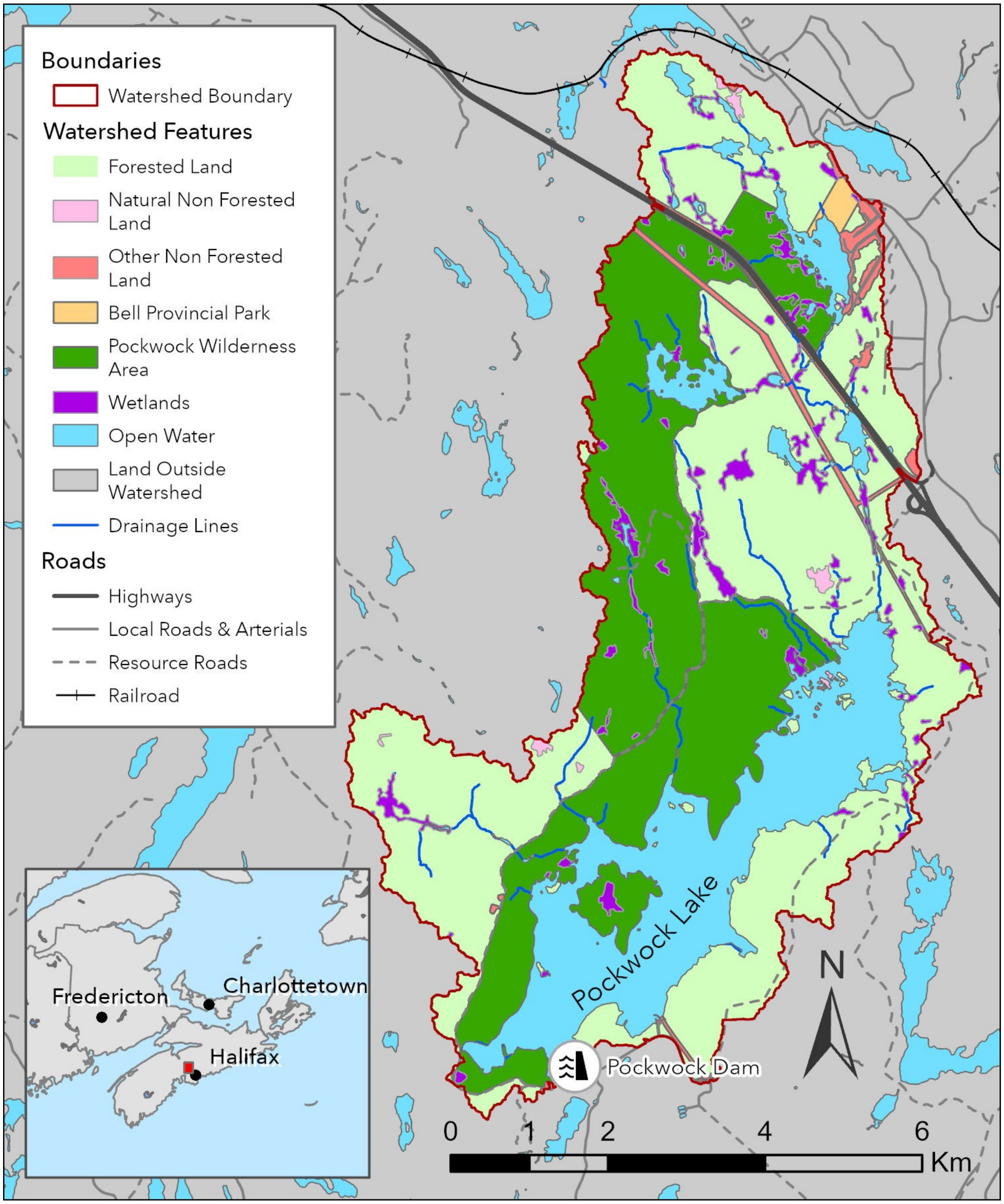

Figure 4.1 The Pockwock watershed (outlined in red) including (inset) the location of the watershed (red box) within Atlantic Canada.

4.2.1.1 Study Area Characterization

The forest and hydrologic properties of the study area were described and quantified using various methods. Classification of forest stand types and soils is described in Foster *et al*. (2024), and was used to calibrate the application of regionally developed, empirical growth and yield curves in the study area. We used wetland boundaries from the province's forest inventory (NSDNRR 2021), representing larger areas that are hydrologically well connected to main flow channels. The watershed contains many smaller wet areas that some research indicates may contribute to DOC export (Creed *et al*. 2003), but these were omitted from this study due to a lack of overland hydrologic connectivity and little research into the contributions of smaller wet areas in this context.

The extent of the watershed, delineation of its catchments, and location of drainage pathways was performed using the Arc Hydro extension to ArcMap (v 10.5) (Esri 2015) and a 1-m resolution digital elevation map (Nova Scotia GeoNova 2012). These results compared favourably to other characterizations of the watershed, including resources available from Halifax Water (2024). Resulting flow paths were manually rectified to ensure conformity to known hydrographic boundaries within the watershed. Five catchments were selected for further study of their water and flows (Figure 4.2; Table 4.1). Only one major catchment was omitted from study, primarily due to the potential influence of a major highway that could mask subtle water quality changes from forest timber management activities. The remainder of the watershed does not hydrologically resolve into perennial tributaries, making monitoring impractical by the selected methods.

*Table 4.1 Breakdown of forested landbase (in ha) in the Pockwock watershed for forest modelling purposes by land classification within each of six monitored hydrologic subcatchments of the watershed. Wetlands include many types and are included in forested lands. The Pockwock Wilderness Area and other exclusions (e.g. wetlands, watercourse buffers, old growth areas) are ineligible for harvest in some modelled management regimes. *S4S1 excluded from totals because it is nested within, and therefore already accounted for by S4S2.*

Land classification	**S1S1**	**S2S1**	**S3S1**	**S4S1**	**S4S2**	**S5S1**	**Total monitored***	**Total watershed**
Total forested land	124	306	121	26	401	260	1,212	4,000
Wetland area	8.8	16.0	1.7	0.8	12.9	19.9	59.3	200.3
% wetland	7.1%	5.3%	1.4%	3.1%	3.2%	7.6%	4.8%	5.0%
Pockwock Wilderness Area	*--*	*280*	*45*	*--*	*1*	*150*	*476*	*1,600*
Other exclusions	*22*	*--*	*6*	*2.0*	*31*	*25*	*84*	*345*
Total protected	22	280	51	2.0	32	175	559	1945
Total eligible for harvest	102	26	70	24	369	85	652	2055

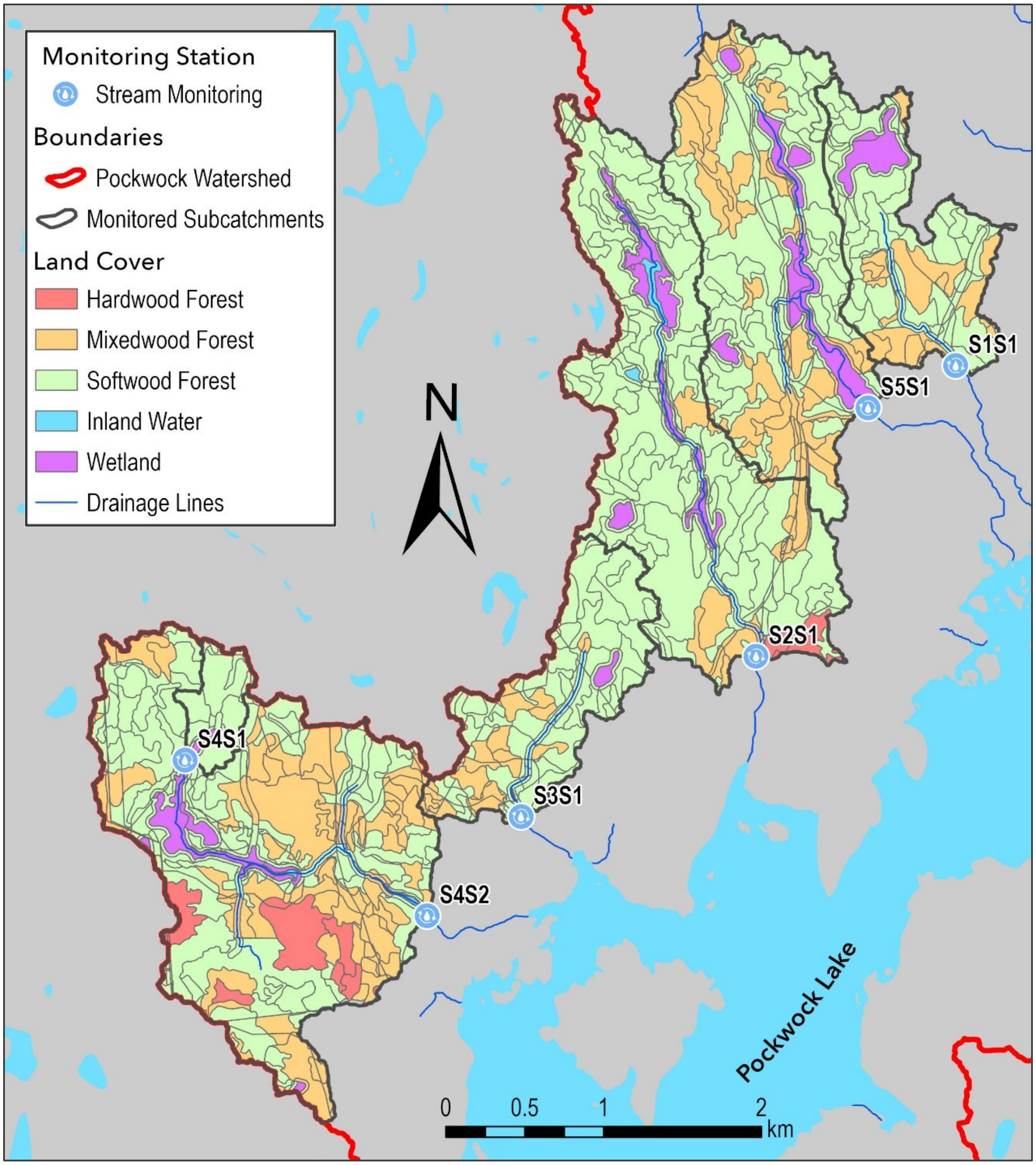

Figure 4.2 The Pockwock watershed including subcatchments, forest or land cover type, drainage lines, and stream monitoring points. Stream monitoring points correspond to the portion of catchments that flows to them, e.g. Stream 1, site 1 = S1S1. Stream 4 has two nested subcatchments, monitored by S4S1 and S4S2. Drainage lines include unresolved but dominant flow paths to perennial streams of any order.

Water flow and quality were monitored for six subcatchments within the five selected catchments between 2018 and 2023 (Figure 4.2), named for their catchment and the monitoring site, e.g. stream 1 site 1 (S1S1). Water depth was measured *in-situ* with HOBO UL20L-04 water level data loggers installed in stilling wells. Researchers periodically measured flows following precipitation events year-round using a SonTek

FlowTracker handheld acoustic doppler velocimeter (YSI Inc. 2024) or Gurley Pygmy Price current meter (Gurley Precision Instruments 2018) and the velocity-area method (Rantz 1982). Water quality samples were collected during the same visits and later analyzed for DOC concentration either internally or by commercial lab. Annual DOC loading was determined using LoadRunner (Booth *et al*. 2007), a GUI-based implementation of the FORTRAN-based tool LOADEST (Runkel *et al*. 2004). Ratings curves were developed for each of the six monitoring locations using between 9 and 23 depth and flow measurements for each, providing continuous flow records for the study period between June 2018 (or May 2019 for S5S1) and July 2023, herein referred to as observed flows (Rantz 1982).

Timber harvests were conducted in subcatchments S1, S4, and S5, and included varying levels of harvest intensity both in terms of area treated and proportion of trees removed (Table 4.2, see McGrath *et al*. (2021) for descriptions of the harvest types employed). All harvests removed only merchantable stem volume, leaving branches and tops (slash) on site. Additionally, harvest machinery used low pressure tires and harvest operations and trucking were suspended during periods of high precipitation to minimize soil disturbance. No site preparation (intentional mineral soil disturbance) was carried out following harvest, and the sites were allowed to regenerate naturally.

Table 4.2 Summary of timber harvests conducted in the Pockwock watershed over the study monitoring period within each subcatchment including the total subcatchment area, harvest methods employed, years of harvest operations, total area treated within each subcatchment and corresponding proportion of area treated, and the level of basal area retention within treated areas.

Subcatchment	S1S1	S5S1	S4S1	S4S2
Subcatchment total (ha)	115	236	25	385
Harvest method(s)	Group selection	30% retention	Thinning & selection	
Harvest year(s)	2019	2019	2020/2021	2020/2021
Harvested area in subcatchment (ha)	1.3	2.2	16.0	34.0
Subcatchment harvested	1.1%	0.9%	63.9%	8.8%
Retention within harvested patches	2%	0%	58%	53%

4.2.2 Data Sources and Processing

The majority of data management, calculations, and modelling was handled in R-Studio (Posit Software 2023) using the R programming language and a variety of packages for R, including several from the core tidyverse collection (Wickham *et al*. 2019) plus lubridate (Grolemund and Wickham 2011), data.table (Dowle and Srinivasan 2003), Rcpp (Eddelbuettel and Francois 2011), and zoo (Zeileis and Grothendieck 2005).

Additional data processing was conducted in Microsoft Excel version 2401 for Windows (Microsoft Corporation 2023).

4.2.2.1 Climate Data

Weather data from a locally maintained station near the Pockwock watershed provided year-round temperature and precipitation measurements every 30 minutes from 2018 to 2023. We derived a baseline future climate scenario using historical data obtained from climatedata.ca including daily temperature and precipitation records for the Halifax International Airport (YHZ) covering 1981-2020 (ClimateData.ca 2024). For the baseline scenario, this period was repeated until the year 2200, simulating a varying climate with a stable trajectory over long periods.

Alternative future climate scenarios of daily temperature and precipitation to the year 2100 were retrieved from climatedata.ca, a Canadian government and NGO partnership (ClimateData.ca 2024). Of the several available global climate models (GCMs) available, two were selected based on the recommendations of the Pacific Climate Impacts Consortium for application in Eastern Canada (Pacific Climate Impacts Consortium 2024). The two selected scenario datasets from the NorESM2-LM and GFDL-ESM4 models were obtained from the Canadian Downscaled Climate Scenarios – Multivariate (CMIP6) dataset (Cannon *et al*. 2015). From the available shared socioeconomic pathways (SSPs), the two available extremes were selected for each GCM, SSPs 1-2.6, which represent a future of “Sustainability”, and 5-8.5, representing “Fossil-fueled development” (O’Neill *et al*. 2017; Riahi *et al*. 2017). Climate scenarios were extended an additional 100 years by replicating the last 20 years of the projected data set (2080-2100) until the year 2200 (Figure 4.3). This represents a stabilization of climate and will allow us to determine if climate stabilization results in DOC stability, or if DOC changes continue due to lags in soil biogeochemical processes.

Of the compiled future climate scenarios, NOR-ESM2 presents warmer future MAT than comparable SSPs from the GFDL-EMS4 GCM. Intra-decadal variation in MAT changes little over time (Figure 4.3). Potential evapotranspiration (PET), which is heavily influenced by MAT, follows similar trends both in terms of direction, relative order, and amount of intra-decadal variation. Precipitation increases slightly in all except the baseline scenarios, and variability seems to increase with time in each of the non-baseline scenarios (Figure 4.3). The severity of high-precipitation years and the frequency of drought years is particularly notable.

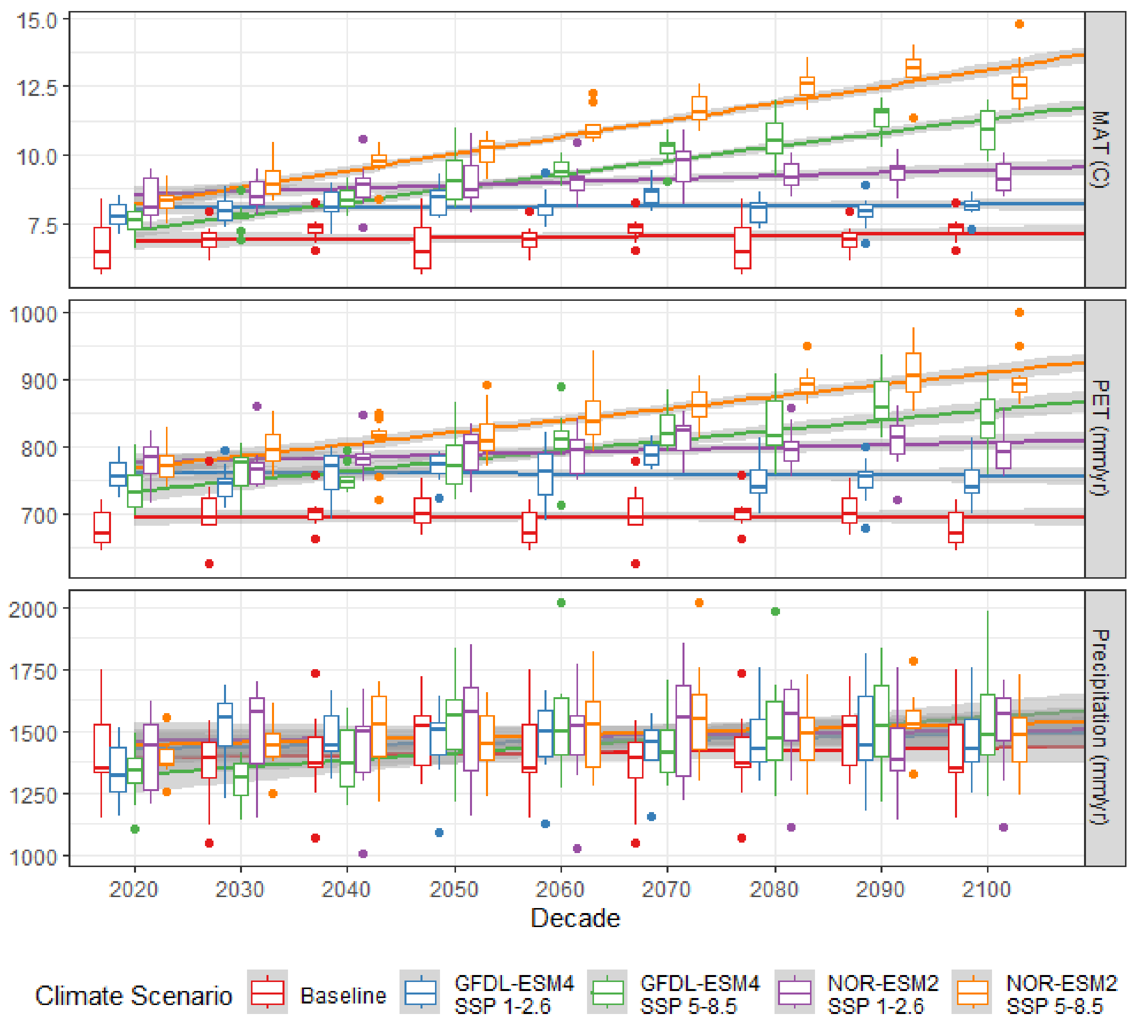

Figure 4.3 Decadal ranges of mean annual temperature (MAT), potential evapotranspiration (PET), and precipitation regimes for five future climate scenarios including two global climate models (GFDL-ESM4/NOR-ESM2) each with two shared socioeconomic pathways (SSP 1-2.6/5-8.5), and one baseline scenario assuming no change. Years on the x-axis indicate the first year in the decade represented until 2100-2109. Lines represent a linear regression of annual means with a 95% confidence interval indicated by the shaded band above and below the line, dots represent outliers.

4.2.3 Modelling

Modelling for this study was carried out in three phases using the data described above and is described in greater detail below. Calibrated hydrologic models of each subcatchment provided estimates of annual flows during the calibration and forecast periods. Forest growth and C modelling provided estimates of C from a variety of possible donor pools during the calibration and forecast periods. Outputs from the calibration period of each of these modelling tasks were used to calibrate a DOC export model for use in forecasting. The following subsections provide greater detail (see Figure 1.1 for an overview of steps involved in the model framework).

4.2.3.1 Hydrology

The HBV-light model (Seibert and Vis 2012) was calibrated for each of the six monitoring locations within the five subcatchments, operating on a daily time step using continuous flow records from a ratings curve generated from discrete flow measurements and 2018-2022. Evapotranspiration, required for the HBV-light model, was calculated using the Hargreaves method in both the calibration and forecast periods. A one-year warm-up period preceded the calibration period and the model's performance was determined with the Nash-Sutcliffe efficiency (NSE) score based on a hydrologic year from 1 October – 30 September. Model parameters were calibrated with HBV-light's built-in genetic-algorithm-based graph partitioning algorithm (GAP simulation), allowed to run for 7,500 runs plus 1,000 runs for local optimization (Seibert 2000). Calibrated parameters were applied to the five forecast climate scenarios including two GCMs each with 2 SSPs, plus the baseline scenario. A two-year overlap at the start of each scenario run (2021-2023) was included using observed precipitation and flows to ensure correct model function before use of climate scenario data (4.2.2.1 Climate Data) from 2023 onwards.

4.2.3.2 Carbon

A forest growth model predicted future forest conditions under different management regimes, as described in Foster *et al*. (2024). Using a current inventory of the study area forest (NSDNRR 2022), stands were grown on an annual timestep with the stochastic application of both natural and anthropogenic disturbances based on eligibility criteria. Natural disturbance rates (NDR) were informed by relevant literature (esp. Taylor *et al*. 2020; MacLean *et al*. 2022), but modified to reflect patterns of NDR management specific to a source water supply such as fire suppression and post-disturbance salvage logging. For simplicity, clearcuts were used as the only harvest technique, with varying return intervals and applied to either the portion of the forest legally eligible for harvest, none, or all forested parts of the study area to represent the management extremes. Approximately half of the study area (568 of 1,128.7 ha) is legally eligible for harvest under current regulations (Table 4.1). Eligibility for harvest was also determined by a stand's growth stage, becoming harvestable when it reached peak mean annual increment (MAI). Previous work revealed that nuances associated with partial harvests

(harvests in which trees are retained throughout the harvest area, see McGrath *et al.* 2021 for further detail) are not likely to produce differentiable C outcomes for the purposes of modelled hydrologic export and that extreme cases would better represent the range of possibilities. Harvest amounts follow an annual allowable cut (AAC) model (Natural Resources Canada 2020), where the target return interval (50 or 100 years) is the denominator in the proportion of the forest harvested each year.

A custom implementation of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz *et al*. 2009) predicted transfers of C from living biomass to dead organic matter (DOM) pools at each annual timestep, plus C transformations, movement between DOM pools, and C losses to the atmosphere. CBM-CFS3 assumes that all C leaving the modelled system is via gaseous losses to the atmosphere or harvested product removals. Previous work by Smiley & Trofymow (2017) used CBM-CFS3 to estimate the proportion of losses that are exported as DOC rather than atmospherically, as explicitly assumed within the model's documentation. Smiley & Trofymow (2017) identified "more mobile sources of DOM" as important possible sources of highly labile C, such as forest floor litter (Smiley and Trofymow 2017: 14), especially following disturbances like harvesting or natural mortality. Our custom implementation of CBM-CFS3 permits the consideration of all DOM pools as possible sources of C for hydrologic export.

Our implementation of CBM-CFS3 uses outputs from a forest growth model run in R, and makes calculations in a version of C++ written for use in R through the Rcpp. Calculations of C transfers between pools and C transformations are made annually, and atmospheric losses from each of nine DOM pools are totaled annually by subcatchment. DOM pools have specific, temperature-dependent decay rates that affect the rate of C loss to the atmosphere, and possibly hydrologically (Table 4.3). For simplicity, some pools' atmospheric losses were grouped based on the relative decay rate of the individual pools for use in later analysis (Figure 4.4).

Table 4.3 List of dead organic matter (DOM) pools from the Carbon Budget Model of the Canadian Forest Sector (Kurz et al. 2009), corresponding descriptions of the material comprising each pool, and equivalent pool from IPCC Good Practice Guidelines (IPCC 2003). The base decay rates, from Kurz et al. (2009), is modified by mean annual temperature to determine the decay rate of each respective pool.

DOM pool	Description	IPCC carbon pool	Base decay rate
Slow AG	Forest floor F & H horizons	Litter	0.015
Slow BG	Humified organic matter in mineral soil	Soil organic carbon	0.0033
Medium	Coarse, dead woody material	Dead wood	0.0374
Fast AG	Fine and small woody debris and dead coarse roots (≥5 mm & <75 mm) in forest floor	Litter	0.1435
Fast BG	Dead, coarse roots (≥5 mm) in mineral soil	Soil organic carbon	0.1435
Very fast AG	Forest floor litter horizon and dead, fine roots (<5 mm)	Litter	0.355
Very fast BG	Dead, fine roots (<5 mm) in mineral soil	Soil organic carbon	0.5
Stem snags	Standing dead stems (of merchantable volume) including bark	Dead wood	0.0187
Branch snags	Standing dead branches, including bark		0.0718

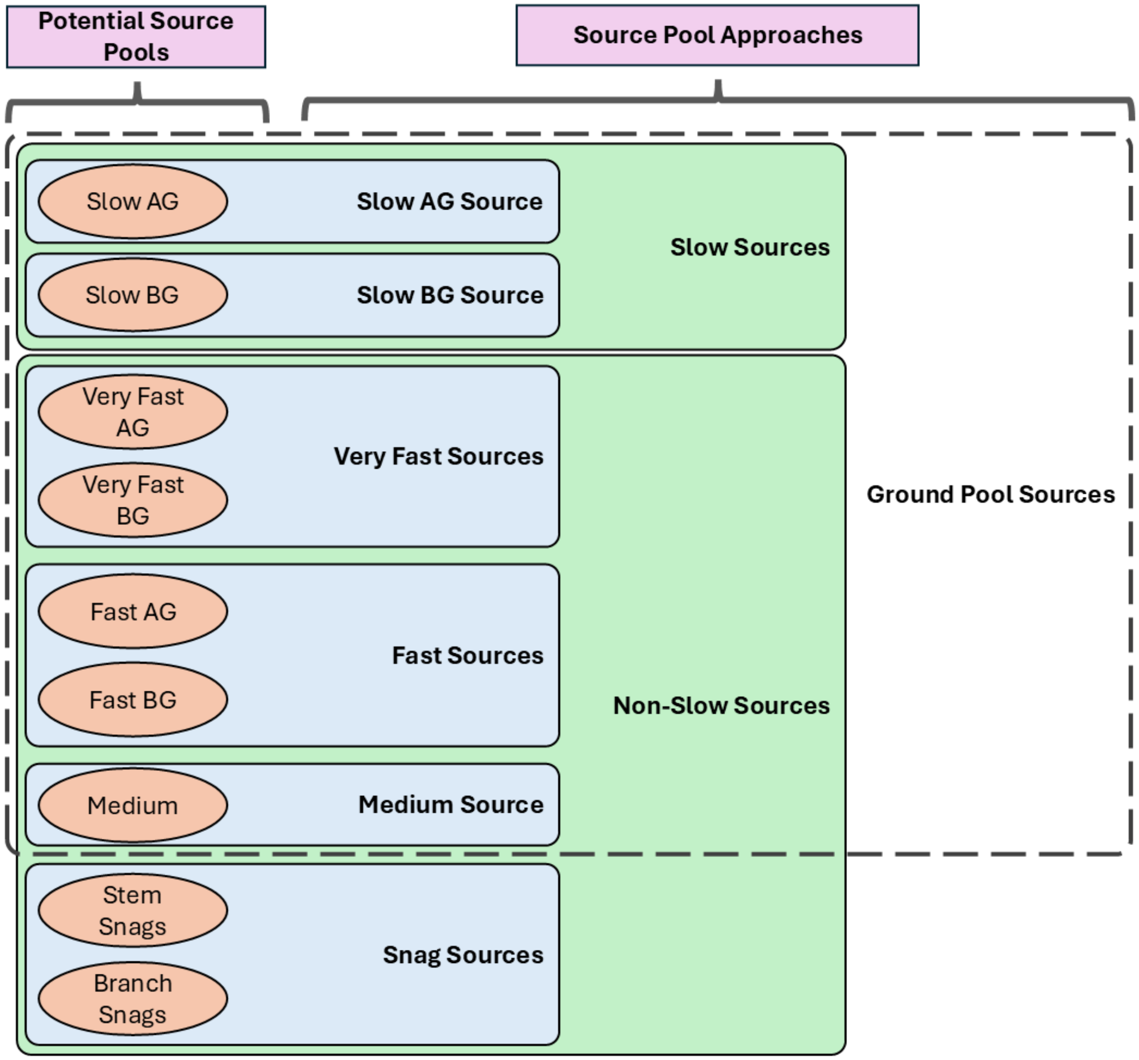

Figure 4.4 Dead organic matter pools (potential source pools) from the Carbon Budget Model of the Canadian Forest Sector (Kurz et al. 2009) and the various combinations used to predict dissolved organic carbon loading (source pool approaches). DOM pools are named by their relative decay rate and whether they are above (AG) or belowground (BG).

The selected forest growth and C modelling methods only permit decay rates to be affected by differences between climate scenarios. CBM-CFS3 determines decomposition rate as a function of temperature, but does not account for moisture conditions, and neither precipitation nor temperature are directly accounted for in stand growth models. Mean annual temperature was calculated for each simulation year for each climate scenario and used in the custom CBM-CFS3 implementation to vary decomposition rates.

4.2.3.3 Estimates of DOC Export

Using discrete measurements of stream water [DOC] coupled with stream flow and estimated C respired to the atmosphere from various DOM pools during the calibration period (2018-2022), we calibrated a DOC export model that partitioned a fraction of respired C to DOC export using a variety of DOM source pools approaches. Equation 1, based on Eckhardt & Moore's (1990) model of DOC production, was previously successfully used in this forest region by Zhang *et al*. (2013), and modified for use in this study area based on data availability.

Equation 1:

$$DOC_{export} = \overbrace{b_{DOCu}(DOC_{PU})(1 - F_{wet})Q^a}^{\textit{Upland contributions}} + \overbrace{b_{DOCw}(F_{wet})Q^a}^{\textit{Wetland contributions}}$$

Where:

- DOC_{export} is the amount of C exported as DOC from the area of study (Mg yr^{-1});
- b_{DOCu} is a parameter for DOC release from upland areas (unitless) to be calibrated;
- DOC_{PU} is potentially soluble C assumed to be lost to respiration in CBM-CFS3 (Mg yr^{-1});
- Q^a is stream flow (m^3) raised to an additional parameter for DOC release (unitless) to be calibrated;
- F_{wet} is the proportion of the landscape classified as wetland; and,
- b_{DOCw} is a combined parameter for DOC release from wetland areas (unitless) to be calibrated.

This model of DOC export predicts that DOC_{export} for a given period is a function of the mobilization of C from available, soluble pools in upland and wetland portions of a catchment. For the upland portion, the coefficient b_{DOCu} is to be calibrated. The potential pool of C to be exported hydrologically (DOC_{PU}), was derived from C that CBM-CFS3 assumes is lost to the atmosphere through respiration; different combinations of source pools are considered as possible approaches to estimating DOC loading. In the wetland portion of the landscape, the potential pool of soluble C is unknown and therefore b_{DOCw} was calibrated alone, representing both the potential pool and release coefficient as unity. This assumes that wetland DOC production will not change over time which is necessary given limited data about the wetlands in this area, or understanding of how climate change will affect their C dynamics and potential DOC export. F_{wet} was determined from provincial records of wetlands in the Pockwock watershed.

DOC export during the calibration period and potential upland DOC production estimated from CBM-CFS3, were used to calibrate b_{DOCu}, b_{DOCw}, and a both by subcatchment and by year. These parameters were derived in Microsoft Excel using the Solver add-in's generalized reduced gradient (GRG) non-linear method (Frontline Systems, Inc. 2008), optimizing for the lowest sum of squared error value in Equation 2.

Equation 2: $$x^2 = \sum \frac{(P_j - O_j)^2}{err^2}$$

Where:

- x^2 is the cumulative sum of error from all estimates versus observations;
- P_j is individual estimates from the model;
- O_j is individual observations; and,
- err^2 is standard error of the estimate versus observation.

Eight C source pool approaches were tested to determine the feasibility of any one or combination thereof being the source of solubilized C exported as DOC (Figure 4.4). Similar to the work of Smiley & Trofymow (2017), we examined the slow above- (AG) and belowground (BG) pools both separately and together. Additionally, we examined other DOM pools grouped by decay rate class including very fast AG and BG together, fast AG and BG together, and branch and stem snags together. An approach combining all non-slow pools was also used to examine faster decay rates all together. Finally, a likely scenario was tested that combined all non-snag pools, referred to herein as 'ground pools' (Figure 4.4), in recognition that all non-snag pools lie on or near the ground.

4.3 Results

4.3.1 Measurements and Model Calibration

DOC concentrations in control and harvest treatment subcatchments showed similar patterns of interannual variation (Figure 4.5), indicating that harvesting did not have an acute impact on DOC export. On this basis, calibration of the DOC export model proceeded using all measurements both pre- and post-harvest.

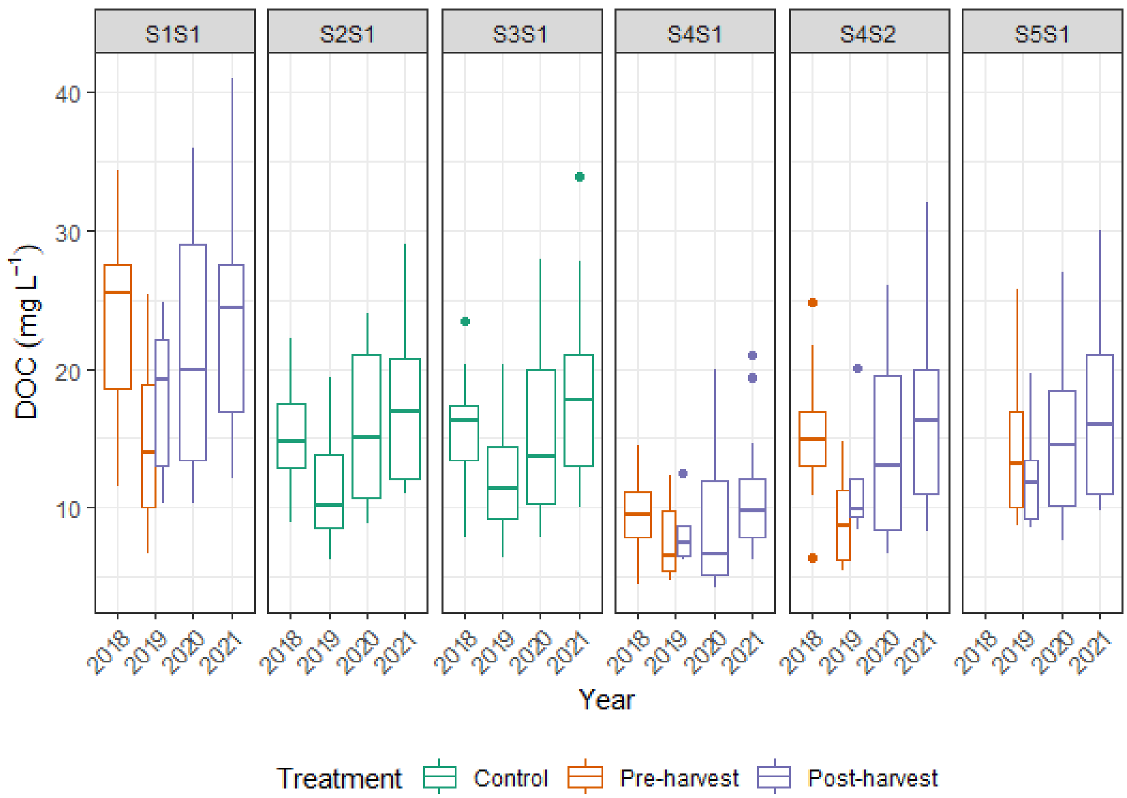

Figure 4.5 Dissolved organic carbon (DOC) concentrations during the calibration period at six points (S1S1-S5S1) in five monitored subcatchments, with S4S1 upstream of S4S2. Treatments describe the subcatchment's condition, either as a control (no harvesting during calibration period) or pre- or post-harvest as part of planned forest management. Dots represent outliers.

4.3.1.1 Hydrologic Model Calibration

HBV was successfully calibrated with NSE scores between 0.44 and 0.70 (Table 4.4). The lowest NSE scores come from the subcatchments with the lowest number of flow observations used (S5S1), smallest drainage area (S4S1), and the highest observed mean annual flow (S3S1, S4S1, and S5S1). These differences are likely caused by an overestimation of observed flows due to poor characterization of high-flow conditions on the ratings curve, especially of these three subcatchments. Scores for NSE are typically deemed satisfactory if between 0 and 1 (Moriasi *et al*. 2007), with scores > 0.5 often being deemed good, rather than simply satisfactory (Houska *et al*. 2014).

Table 4.4 Summary of key hydrologic modelling inputs and outputs for six study subcatchments in the Pockwock Watershed study area. These include the number of flow observations used in generating a ratings curve, mean annual flow in mm and m^3, the difference between flows calculated from ratings curves and depth records (Q_{obs}) and simulated by HBV as calibrated (Q_{sim}), and the Nash-Sutcliffe efficiency (NSE) score for model performance.

Monitoring station	Subcatchment land area (ha)	% wetland	Flow obs. used (n)	Observed mean annual flow (mm)	Observed mean annual flow (m^3x10^6)	Mean difference (Qsim-Qobs, mm yr^{-1})	NSE
S1S1	124	7.1	10	504	0.623	62	0.70
S2S1	303	5.3	19	959	2.936	114	0.66
S3S1	121	1.4	18	*1293*	1.564	224	0.52
S4S1	26	3.1	19	*1310*	0.338	607	0.44
S4S2	399	3.2	21	484	1.941	64	0.64
S5S1	260	7.6	7	*1339*	3.481	671	0.44
TOTAL	**1233**	**4.8**					

A comparison of observed versus modelled flows, especially following substantial precipitation events, shows that observed flows are typically higher than modelled flows (Appendix 2: Annual Hydrographs for Calibration Period). Modelled flows during the calibration period are plausibly more accurate than measured values, especially considering the improbably high mean annual flow from these three subcatchments (Table 4.4). While the lower NSE score for S3S1, S4S1, and S5S1 (between 0.44 and 0.52) are less than optimal from a water budget perspective, they are satisfactory for the purposes of scenario modelling of relative constituent loading.

4.3.1.2 DOC Export Model Calibration

Monitored subcatchments (Figure 4.2) exhibited differing DOC concentrations ([DOC]) during the monitoring period, 2018-2022 (Figure 4.6). S1S1 produced the highest [DOC] (mean 19.8 mg L^{-1}) while S4S1 produced the lowest (mean 8.8 mg L^{-1}). S1S1 [DOC] were significantly different from all other subcatchments: S2S1, S4S1, and S4S2 ($p \leq 0.0001$); S3S1 ($p \leq 0.001$); S5S1 ($p \leq 0.01$). Additionally, S2S1 is significantly different from S4S1 ($p < 0.0001$), S3S1 from S4S1 ($p < 0.0001$), and S4S1 from S4S2 and S5S1 (both $p < 0.0001$. Linear regression demonstrated no significant relationship between [DOC] and total drainage area ($p > 0.1$, adjusted R2 < 0.001) and a significant positive relationship with the proportion of wetland area in each subcatchment, but with a high residual ($p <0.0001$, R2 = 0.053).

Subcatchments S5S1 and S2S1 export the highest amounts of DOC annually, with means of 57.5 and 51.1 Mg yr-1, respectively (Figure 4.6). The largest subcatchment, S4S2, exports significantly less (mean 30.2 Mg yr^{-1}) C than the highest-exporting subcatchments ($p \leq 0.05$) (Figure 4.6). The lowest exporting subcatchments, S4S1 and S1S1, had mean exports of 4.6 and11.5 Mg C yr^{-1}, respectively. Linear regression of annual DOC exports by subcatchment finds a positive relationship with the proportion of wet area per subcatchment (adjusted $R^2 = 0.17$, $p \leq 0.05$), and a stronger positive relationship with total area (adjusted $R^2 = 0.37$, $p < 0.01$).

Mean annual DOC yield (DOC export normalized by unit area) for the study area differed among catchments during the calibration period (2019-2022 for all subcatchments except for S5S1, 2020-2022, Figure 4.6). The largest subcatchment, S4S2, exports the lowest C yield (mean 7.74 g m^{-2} yr^{-1}) and S5S1 (third largest area) exports the highest C (mean 25.2 g m^{-2} yr^{-1}). S4S2 has significantly lower DOC yield C than subcatchments S2S1 and S3S1 ($p \leq 0.01$) and S4S1 ($p \leq 0.05$), the upstream nested subcatchment. Additionally, S3S1 has significantly higher DOC yield than S1S1 ($p \leq 0.05$), a similarly sized subcatchment. All streams combined have a mean annual DOC yield of 16.4 g m^{-2} yr^{-1} (median 15.7 g m^{-2} yr^{-1}), with a standard deviation of 7.88. Linear regression of annual DOC yield by subcatchment found no relationship with the proportion of wet area or the total catchment area (both $p > 0.1$).

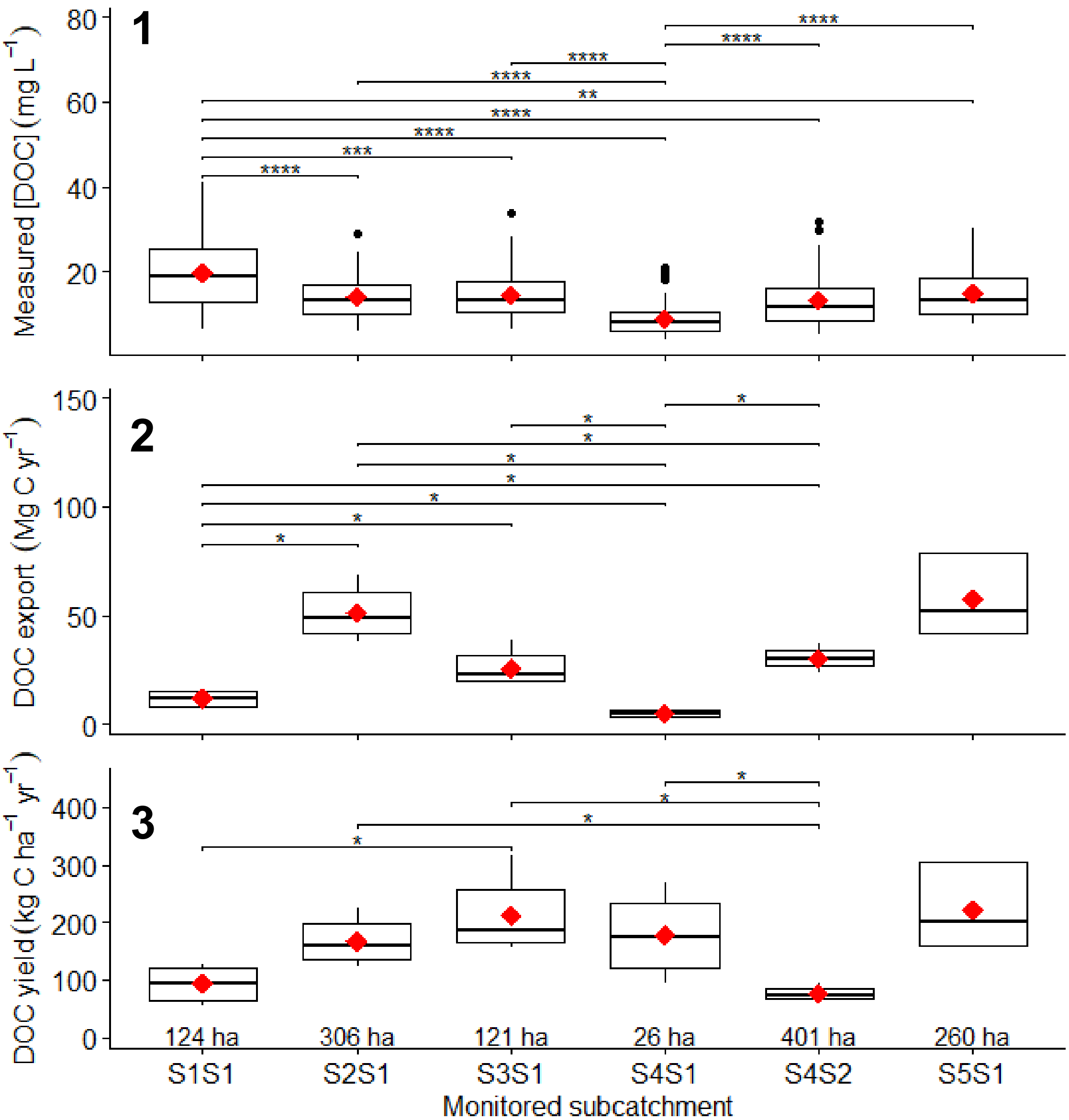

*Figure 4.6 Dissolved organic carbon (DOC) concentration (1), total annual carbon (C) export as DOC (2), and C exported per unit area (DOC yield, 3) from 2019 to 2022 in six monitored subcatchments (stream 1 site 1 (S1S1) through stream 5 site 1 (S5S1)) of the study area, including means indicated by a red diamond. Significant differences in means, including significance levels, are indicated above the boxes. Significance values of p for comparisons are: **** ≤ 0.0001; *** ≤ 0.001; ** ≤ 0.01; * ≤ 0.05; others are not significant, > 0.05.*

Across the five primary monitored subcatchments from 2019 to 2022, the hydrologic DOC export totals were 120, 129, 167, and 230 Mg yr^{-1} (Table 4.5). DOC yield from across the study area for the same period was 126, 106, 138, and 190 kg C ha^{-1} yr^{-1} Records from 2018 are excluded from annual loading totals as measurements began midway through the year.

*Table 4.5 Annual dissolved organic carbon (DOC) export and yield for five monitored subcatchments in the Pockwock watershed study area. Totals under annual yield represent average yield for the entire study area measured in that year. *S5S1 omitted from 2019 total as flow measurements in this subcatchment began midway through the year; +S4S1 omitted from all annual totals, counted within S4S2.*

	Annual total DOC export (Mg C yr^{-1})					Annual DOC yield (kg C ha^{-1} yr^{-1})				
	2019	2020	2021	2022	Mean	2019	2020	2021	2022	Mean
S1S1	15.6	6.9	9.1	14.3	11	142.8	63.6	83.3	131.2	105
S2S1	45.8	37.8	51.8	68.8	51	160.0	132.0	180.8	240.1	178
S3S1	21.0	18.8	24.2	38.3	26	175.5	156.5	202.1	319.9	214
S4S1+	3.9	2.4	5.2	6.9	5	150.5	93.5	199.6	268.6	178
S4S2	37.4	23.7	30.1	29.5	30	95.9	60.8	77.2	75.7	77
S5S1	*--	41.5	52.0	79.0	58	*--	181.8	227.6	346.0	252
Total	**120**	**129**	**167**	**230**		**126**	**106**	**138**	**190**	

Use of CBM-CFS3-derived respiration values provides the total C assumed to be released to the atmosphere in the calibration period (Table 4.6), here serving as DOC_{PU} (Equation 1). Using each DOM pool as the prospective source of exported DOC, we find that each can fulfill the demand for C to meet observed in-stream masses. Values for $bDOC_U$ are inversely related to DOC_{PU}, requiring a greater proportion of total production in smaller pools to be exported to fulfill observed C loading. Despite a broad range in DOC_{PU} between source pool approaches, model performance (R^2) varies relatively little, ranging from 0.697 for the Medium pool only, to 0.721 for the Snag pool only. Labile C production and mobilization from wetlands, $bDOC_W$, has values ranging from 2.44E-2 to 7.31E-2.

Table 4.6 Inputs, coefficients, and results for calibrating Equation 1 considering various dissolved organic carbon (DOC) source pool approaches, using dead organic matter (DOM) pools (Kurz et al. 2009) individually and in groups, for the Pockwock watershed monitored study area. Values include average respired C across the calibration period (DOC_{PU}), components of Equation 1, the R^2 value for each approach, and the mean percentage of C eligible for export from the indicated pool(s) required to meet the observed export totals.

Source pool approach	Avg DOC_{PU} (Mg C yr^{-1})	$bDOC_U$	$bDOC_W$	a	R^2 of model	% total export from upland	Avg % DOC_{PU} exported
Slow BG	310.2	4.90E-05	1.04E-01	5.63E-01	0.717	34.4	14.9
Slow AG	270.2	5.22E-05	1.01E-01	5.66E-01	0.715	33.4	16.6
All Slow	580.4	2.53E-05	1.03E-01	5.64E-01	0.716	34.0	7.8
Very Fast	1703.4	1.08E-05	1.17E-01	5.53E-01	0.722	36.4	2.9
Fast	681.8	1.75E-05	7.49E-02	5.83E-01	0.724	36.4	7.2
Medium	131.8	7.51E-05	7.43E-02	5.88E-01	0.712	32.1	32.8
Snag	79.6	4.06E-04	1.51E-01	5.28E-01	0.739	43.6	74.4
Non Slow	2596.8	6.24E-06	1.02E-01	5.62E-01	0.723	36.4	1.9
All Pools	3177.2	5.02E-06	1.02E-01	5.63E-01	0.722	36.0	1.5
Ground pools	3097.6	5.06E-06	1.01E-01	5.63E-01	0.721	35.8	1.5

The choice of source pool approach, or which DOM pools' respired C to use for DOC_{PU}, affected the estimated proportion of total DOC_{PU} exported hydrologically with the rest lost to the atmosphere (Table 4.6). There is an inverse relationship between DOC_{PU} and the percentage of DOC_{PU} exported hydrologically, with the extremes being Snag, at 75.2% of the 79.6 Mg yr^{-1} DOC_{PU}, and Very Fast at only 2.9% of DOC_{PU}, the largest single flux at 1,703.4 Mg yr^{-1}. When grouped together, the proportion exported hydrologically is even smaller, with only 1.5% of DOC_{PU} from the All Pools approach exported as DOC. Biogeochemically, this study will continue on the assumption that all DOM pools in contact with the ground or part of forest soils will contribute C to hydrologic export. Evidence supporting this principle is explored further in the discussion. The ground pools approach, named as such in Table 4.6, sums DOC_{PU} from both Slow pools, the Very Fast, Fast, and Medium pools for an average DOC_{PU} of 3,097.6 Mg C yr^{-1} during the calibration period years 2019-2022. The calibrated model (R^2 = 0.707; Figure 4.7) predicts that 37.4% of total DOC export comes from upland sources with the remainder, ~64%, from wetlands, and requires that only 1.5% of these source pools' DOC_{PU} is exported hydrologically.

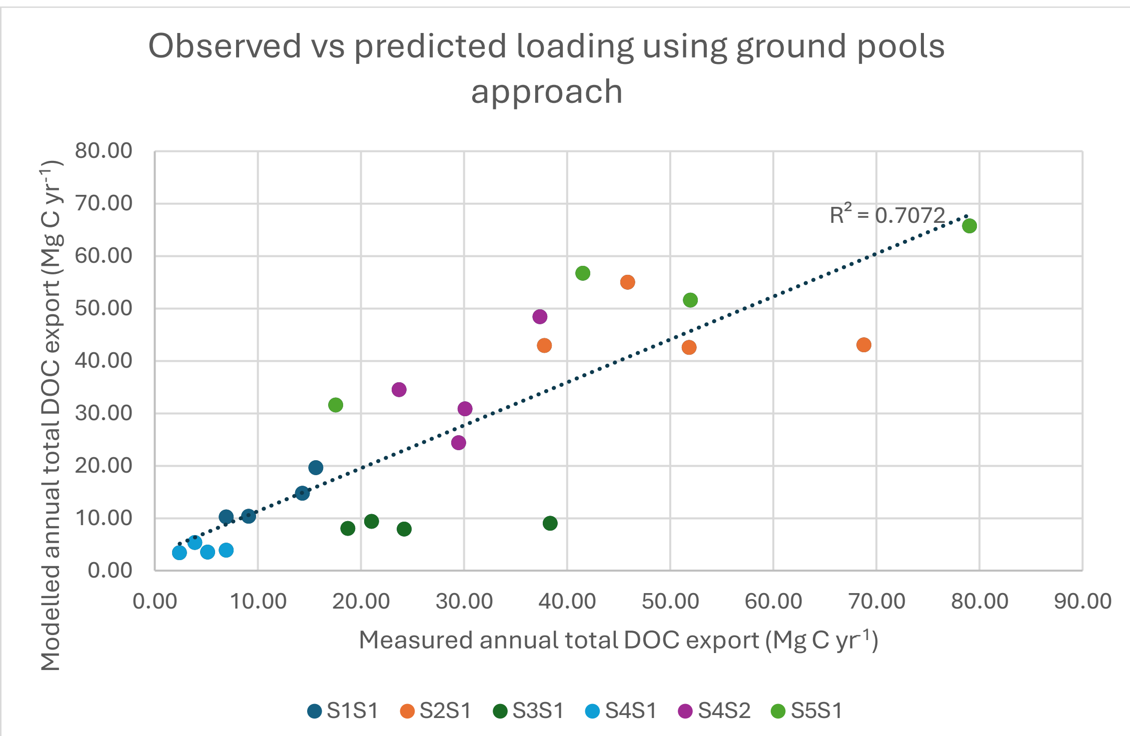

Figure 4.7 Comparison of estimated DOC export from six monitored subcatchments in the study area versus modelled export from calibration of Equation 1 using all dead organic matter (DOM) pools described in Kurz et al. (2009) except for stem snags and branches.

4.3.2 Long-Term Scenario Modelling

4.3.2.1 Future Climate Scenarios

There were subtle differences in annual flow between climate scenarios using the calibrated hydrologic models (Figure 4.8). Flows from the entire study area do not exhibit a clear trend in total volume, although the intra-decadal variation does appear to increase over time in climate change scenarios versus baseline conditions. Slight increases in precipitation (Figure 4.3) appear to be offset by increases in MAT and corresponding PET, resulting in minimal changes in total annual flow.

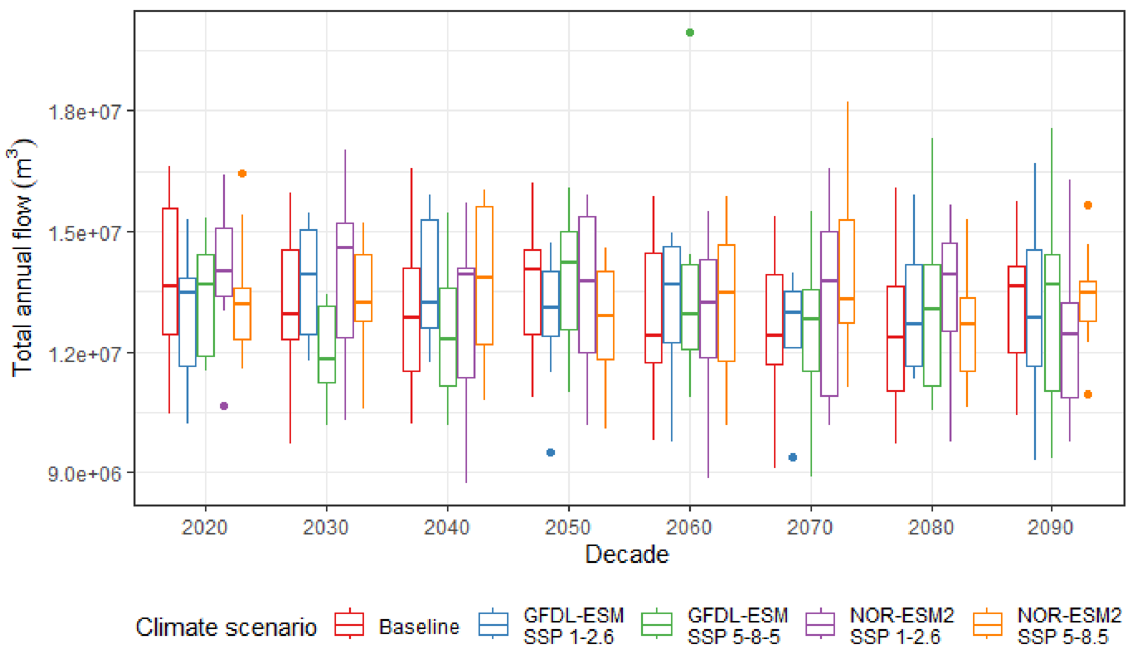

Figure 4.8 Intra- and inter-decadal variability of modelled annual flows for all studied subcatchments of the Pockwock watershed study area under five future climate scenarios: one baseline scenario, and two shared socioeconomic pathways (SSP) for two global climate models, GFDL-ESM4 and NOR-ESM2. Years on the x-axis indicate the first year in the decade represented, up to the decade 2090-2099, after which climate stabilizes.

4.3.2.2 Forest Management and Carbon Pools

Forest growth modelling from 2020-2200 follows similar patterns observed in Foster *et al*. (2024) under a baseline climate scenario (Figure 4.9). Representing the extremes of management, harvesting the entire forested study area landscape at 50-year intervals (harvest-all) and no harvests (harvest none) represent the lowest and highest values, respectively, for both stored C in DOM pools and atmospheric losses through respiration. Clearcut harvesting at 100- (CC-100) and 50-year (CC-50) intervals represents progressively more intensive management that results in both lower C stores in DOM and lower C losses through respiration. Harvested removals represent C exported from the study area for commercial purposes (Figure 4.9). Under the no-harvest management regime, natural mortality from disturbances (wind and pests) is aggressively sought for salvage and removed from the watershed to prevent hydrologic C export and potential risk from fire. As with conventional harvesting, only stems are removed while branches and tops are left behind.

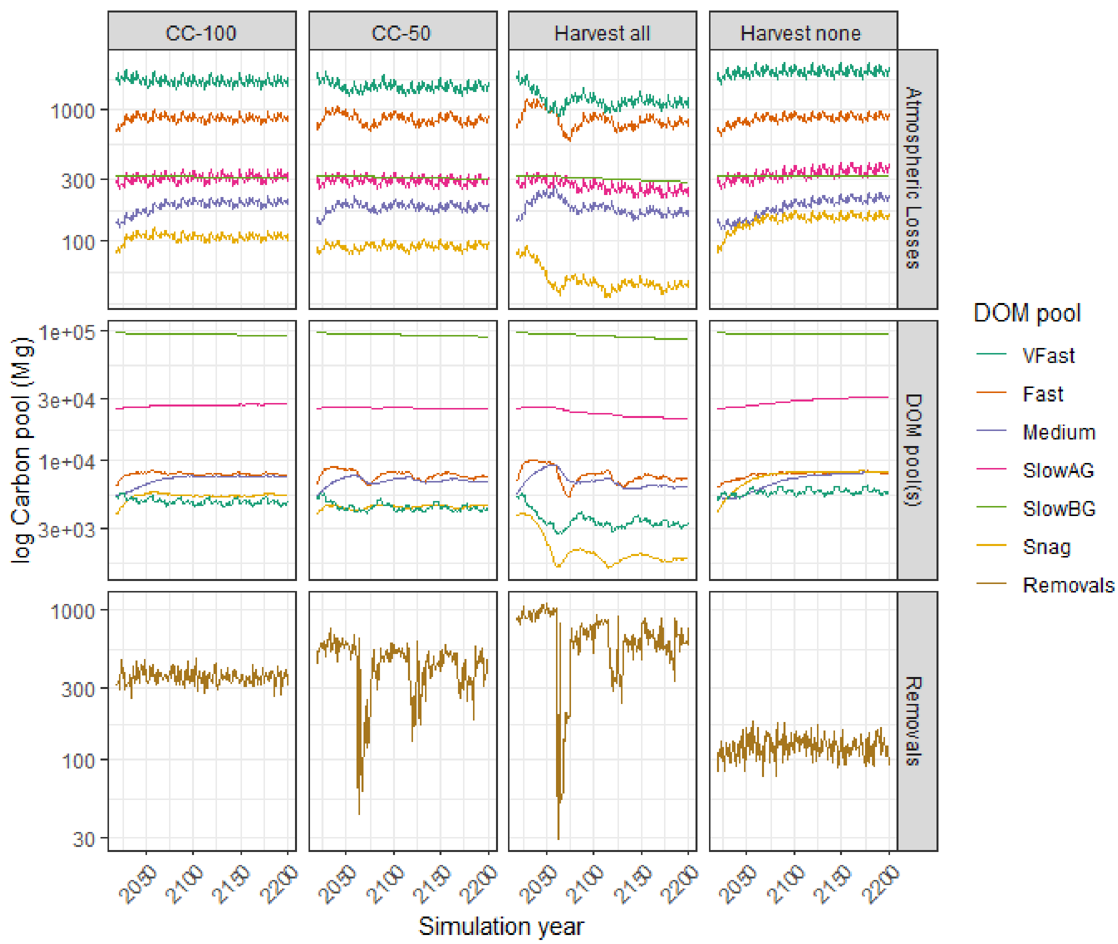

Figure 4.9 Annual total respiration (Atmospheric Losses Mg C yr^{-1}), dead organic matter (DOM) pool stocks (Mg C), and harvested carbon (Removals Mg C yr $^{-1}$) for the four management regimes in all subcatchments of the Pockwock watershed study area (1200 ha). Dead organic matter (DOM) pools are as described in Kurz et al. (2009), grouped by decay rate. Management regimes, presented across columns, include clearcuts (CC) at 100- and 50-year intervals within legally eligible areas, clearcutting at 50 year intervals in the entire watershed, and carrying out no planned harvests.

In both the 50-year clearcut (CC-50) and harvest-all regimes, the harvested removals illustrate a trend seen in both the DOM and atmospheric losses. For both the CC-50 and harvest-all regimes, 1/50th of the forest is harvested annually. Because natural disturbances also reduce the tree population and most stands won't reach harvest eligibility (based on reaching peak MAI) within 50 years, the eligible stand population is exhausted before the simulation's 50th year (Figure 4.10). The CC-100 regime never depletes harvestable stands because all stand types reach peak MAI in under 100 years, and removals from the no harvest regime are solely driven by natural disturbances.

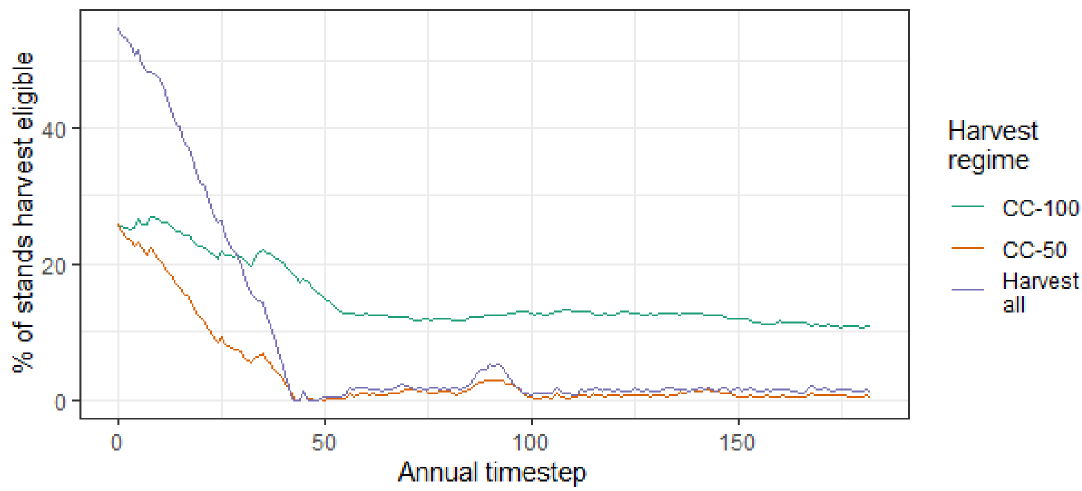

Figure 4.10 Percent of stands eligible for harvest at each timestep of the forest model run that includes planned harvests. All regimes use clearcuts (CC) and use a return interval of either 50 or 100 years; the harvest-all regime disregards legal designations that otherwise render forested areas unharvestable. Eligibility is determined both by legal status and whether a stand has reached its peak mean annual increment.

Climate scenario affects both DOM pool C stocks and accumulated respired C losses to the atmosphere (Figure 4.11). Examining only the CC-100 regime, which represents harvests with a target return interval of 100 years, each graph can be divided into two portions, the first 80 and last 100 years of simulation. In the first 80 years, climate scenarios' MAT and precipitation are changing, which causes shifts in decay dynamics, affecting both DOM and respiration. In the next phase, 100 years of a repeating 20-year weather pattern results in a dynamic equilibrium and stabilization of many pools. Results in Figure 4.11 are represented using local regression smoothing to present trends more clearly.

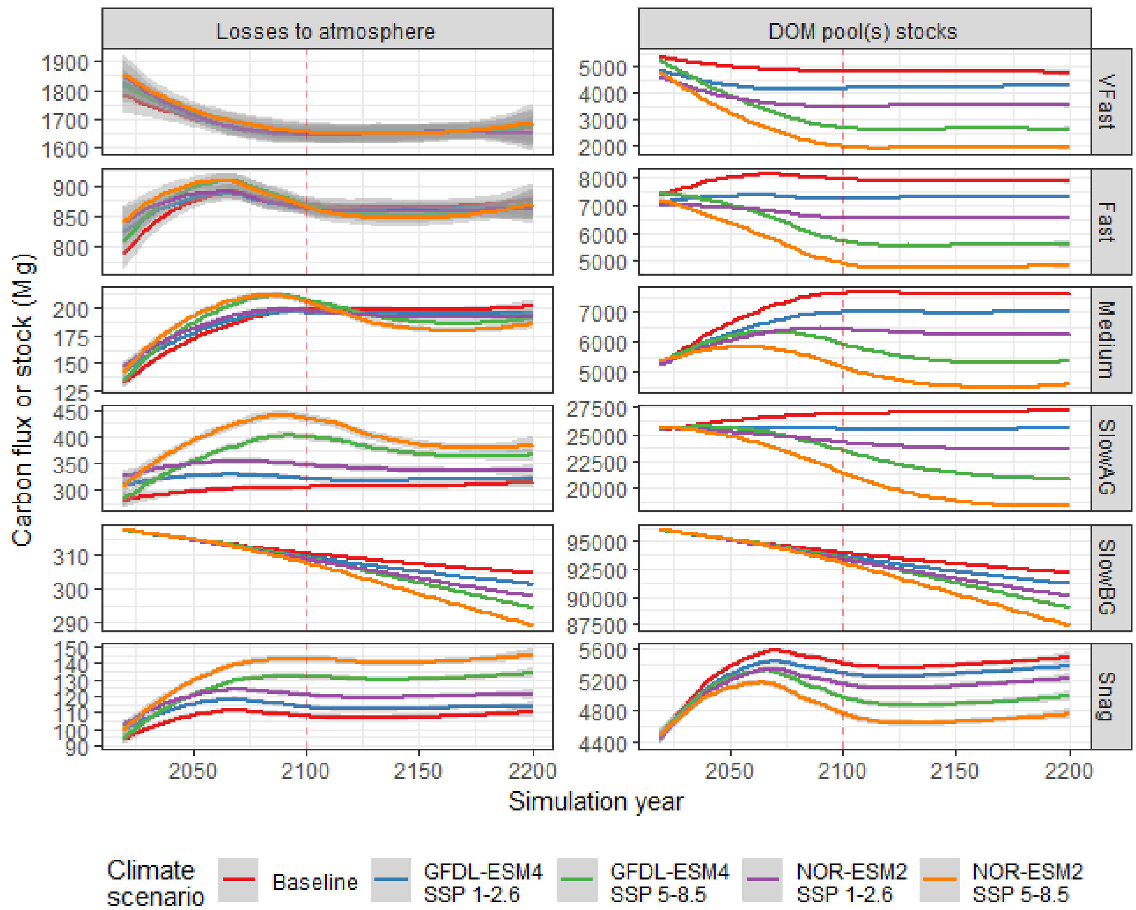

Figure 4.11 Annual trends in accumulated respired C losses to atmosphere and DOM pool C stocks under five climate future scenarios applied to a moderate harvest regime (CC-100, see Figure 4.9) simulation in the study area. Two shared socioeconomic pathways (SSPs) are selected from two global climate models, GFDL-ESM4 and NOR-ESM2, plus a baseline scenario to present a range of future climate effects on C accumulation and atmospheric losses from a variety of dead organic matter (DOM) pools, as defined in Kurz et al. (2009).

All pools begin an immediate shift from antecedent conditions, including the baseline climate scenario, signaling the effects of harvest and climate regime on the landscape. Only the Very Fast and Slow BG DOM pools decrease in all climate scenarios. Due to the temperature-influenced increased rate of decay, the Very Fast pool reduces from approximately 5,680 Mg C at the start of simulation to only 1,560 Mg C in the NOR-ESM2 SSP 5-8.5 scenario, corresponding with a decrease in respiration losses, from 1,860 Mg yr^{-1} to 1,720 Mg yr^{-1} of C in the same scenario. The decay rate applied to the Very Fast pools is as much as an order of magnitude faster than other pools (Table 4.3), meaning it depletes its organic matter quickly. The Fast DOM pool is reduced under more severe climate change (SSP 5-8.5) but is relatively stable in less severe scenarios (baseline and SSP 1-2.6).

Medium DOM pools increase in all but the most severe climate future (SSP 5-8.5), and snag pools increase in all scenarios. Respiration from both these DOM pools increases in all climate scenarios. This coarser, woody material, either on the ground (medium) or standing (snag), is likely to accumulate under less-intensive harvest regimes as trees of varying ages die naturally, standing in place until they naturally fall to the ground (note that only senescence (natural death) leads to snags as pest- or wind-disturbed trees are salvage-harvested in these model runs). This contrasts with more intensive management, demonstrated by the harvest-all regime (Figure 4.9), in which the snag pool is diminished as harvesting minimizes senescence. Alternatively, the medium DOM pool stays relatively stable under more intensive management as retention of branches and tops following harvest replenishes this pool.

The Slow AG DOM pool increases in the baseline scenario, is stable in the GFDL-ESM4 SSP 1-2.6 scenario, and decreases in all other scenarios. These changes correspond with an increase in respiration from the Slow AG pool in all future climate scenarios due to increased decay rates, with the highest increases under the most severe changes (SSP 5-8.5). The Slow BG pool consistently decreases in all future climate scenarios under the CC-100 regime, which causes a similarly steady decrease in respiration from this pool.

4.3.2.3 DOC Export

Total DOC export from the total study area shows a clear, inverse response to management intensity (Figure 4.12), resembling the relationship between atmospheric losses and management regime (Figure 4.9), in which greater management intensity is correlated with lower respiration losses. Most management regime and climate scenario combinations that included harvesting resulted in reduced DOC exports over current conditions. The effect of climate scenario is less prominent than the effect of forest timber management (Figure 4.12). In each management regime, the relative order of DOC export from uplands is maintained between climate scenarios, and management regime affects all scenarios in a similar fashion. The harvest-all regime had higher initial DOC export because of higher initial levels of harvesting increasing DOM pools, increasing the available labile C. Comparing the two most extreme management regimes (Figure 4.13), the effects of both climate scenario and management regime become clearer. More intensive harvesting leads to both lower total DOC export and lower intra-decadal variability. Abstaining from harvests results in the opposite, both higher annual exports and greater ranges of intra-decadal variability.

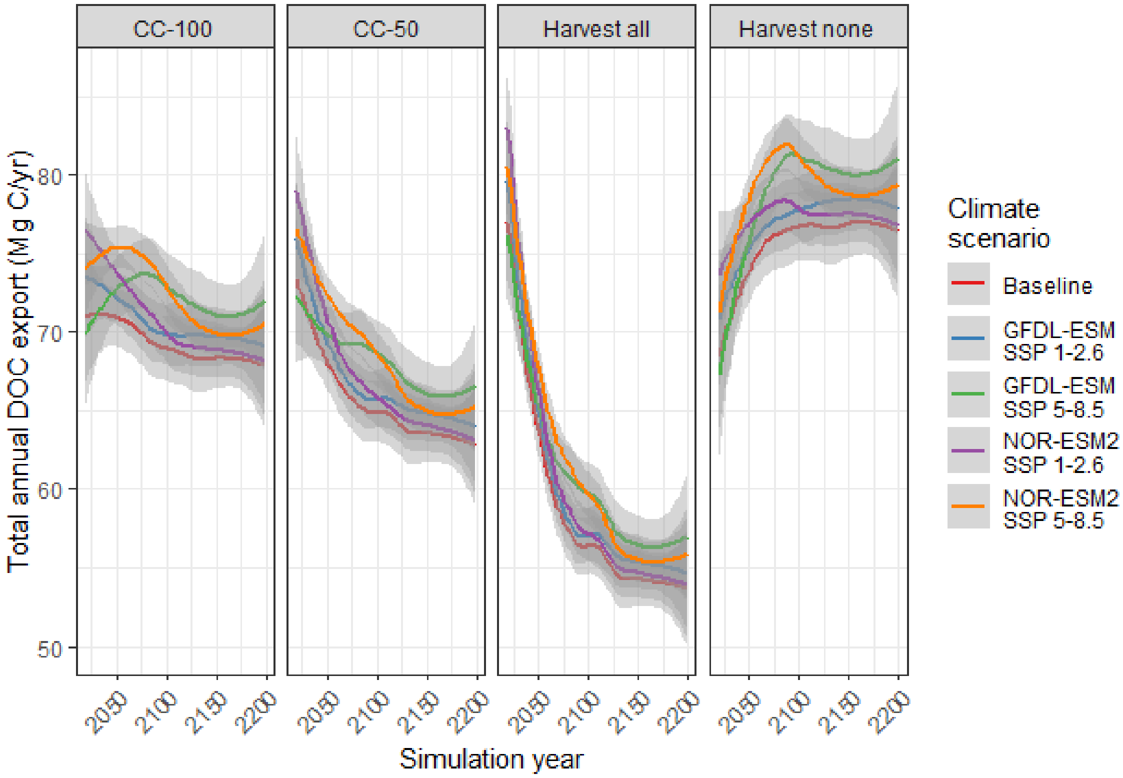

Figure 4.12 Total annual dissolved organic carbon (DOC) exported from the forests and wetlands in the monitored study area under four forest management regimes and calculated using five future climate scenarios including two global climate models, GFDL-ESM4 and NOR-ESM2, with two shared socioeconomic pathways (SSPs) each. Harvest management regimes include harvesting by clearcutting (CC) in all but the harvest-none regime.

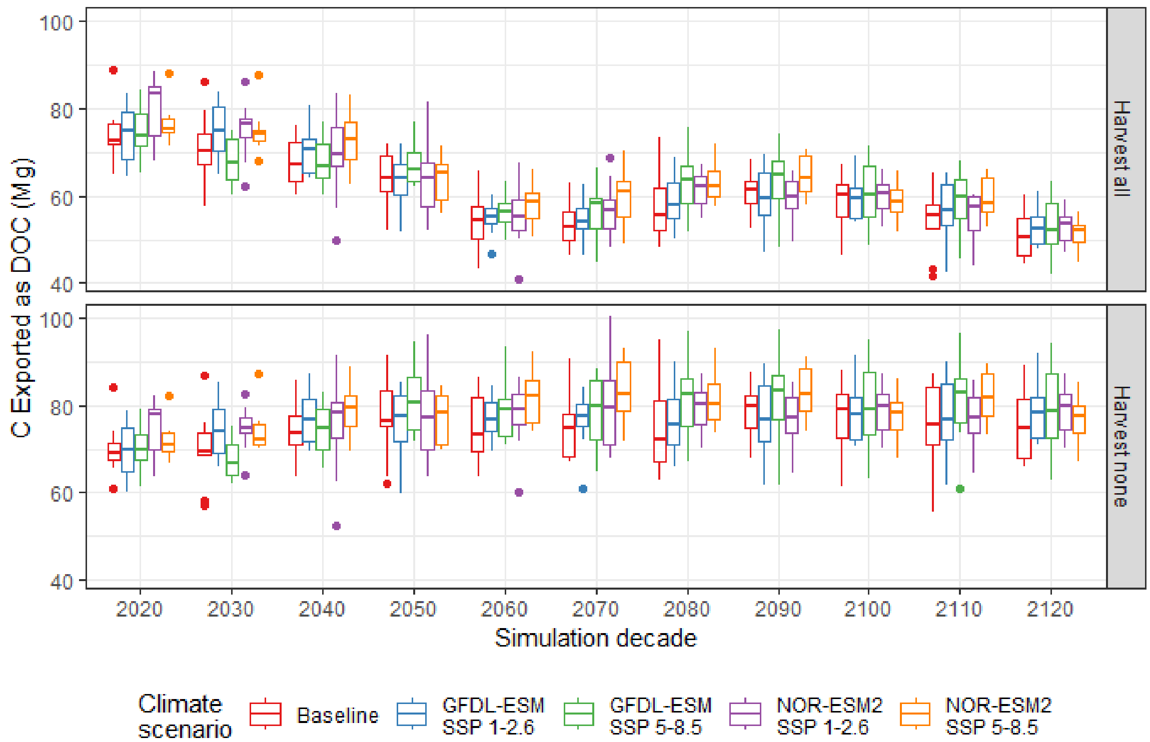

Figure 4.13 Annual dissolved organic carbon (DOC) exports in the Pockwock watershed study area under two forest management regimes and calculated using five future climate scenarios including two global climate models with two shared socioeconomic pathways (SSPs) each. Years on the x-axis indicate the first year in the decade represented, up to the decade 2120-2129, when C export stabilizes under extrapolated future climate scenarios.

4.4 Discussion

In this discussion, we will first look at the process of collecting data, selecting and calibrating models, and the estimates that came from those models with comparisons to other literature. In the second section, we will examine the simulation modelling outcomes with comparisons to other literature, and examine the long-term implications of these findings for the Pockwock watershed.

4.4.1 Measurements, Calibration, and Estimates

4.4.1.1 Hydrologic Modelling

A key challenge in studying the subcatchments of the study area is their small size. With a lag between peak precipitation and peak flows that is as little as a few hours, it was challenging to observe peak flows. Therefore, the high-end of the ratings curve was calculated using surveying and modelling of estimated flows. This likely led to over-estimations of observed peak flows and, especially in S5S1 where the ratings curve was based on only seven observations of flow, the lower NSE scores. Additionally, little is known about sub-surface hydrologic flows both in and out of the monitored subcatchments. These additional sources and sinks of water could be influential in the overall water budget.

Despite difficulty in accurately characterizing these subcatchments, the calibrated hydrologic models for each had NSE scores between 0.44 and 0.70. These scores are classified as satisfactory to good, based on the scheme proposed by Moriasi *et al.* (2007). For the potential utility of a model with such calibration outcomes, the framework proposed by Harmel *et al.* (2014) would suggest that the model is useful for exploratory purposes. In the worst case within this framework, if we characterized model accuracy as low and uncertainty as high, the model "may be useful to highlight range of possible system behaviours and develop hypotheses" (Harmel *et al.* 2014, 46). With this understanding, the calibrated models are suitable for the purpose of generating future runoff scenarios under different climate regimes.

4.4.1.2 DOC Export Measurements and Modelled Estimates

Estimates of the proportion of respired C that is instead exported hydrologically, 1.5% in the ground pools approach, compare favourably to other literature estimates. In a study in western Oregon, Lajtha and Jones (2018) found that approximately 0.5% of mobilized C was lost to streams. While our total proportion is three times higher, observed stream DOC in our study (means ranging from 8.8-19.8 mg L^{-1}) were substantially higher than those in their study (0.6-2.0 mg L^{-1}), suggesting either a higher proportion of C lost hydrologically which aligns with our findings, a greater total supply, or a combination of both.

Our findings for DOC export in the Pockwock watershed are comparable to other studies both regionally and internationally. From the six monitored subcatchments, mean DOC yields across all years from S4S2 (77 kg ha^{-1} yr^{-1}) were the lowest and those from S5S1 (252 kg ha^{-1} yr^{-1}) were the highest. Past studies from this region found total organic carbon (TOC) values of between 16.1 and 123.5 kg m^{-2} yr^{-1}, with a median export rate of 57 kg ha^{-1} yr^{-1} for river basins in temperate regions, with an estimated >95% of TOC as DOC (Clair *et al*. 1994). A different study examining the hydrologically and geomorphically very similar Kejimkujik watershed in Nova Scotia between 1989 and 1997 found DOC export of 137.4 kg ha^{-1} yr^{-1} in a 17.84 km^2 catchment with a wetland area of 53.8% (Creed *et al*. 2008), within the range of values found in our study (77-252 kg ha^{-1} yr^{-1}).

Looking further abroad, Li *et al*. (2015) found similar DOC exports in forests of Southern Quebec, with a high-end estimate of 130 kg ha^{-1} yr^{-1}, which they compared favourably to the results of Eckhardt & Moore (1990), who found a range of 10-180 kg ha^{-1} yr^{-1}. Our findings are also within the range of findings on Canada's west coast, where McNicol *et al*. (2023) found average DOC yields between 21-288 kg ha^{-1} yr^{-1} (mean 73 kg ha^{-1} yr^{-1}) in perhumid forests, and 13-289 kg ha^{-1} yr^{-1} (mean 49 kg ha^{-1} yr^{-1}) in seasonal forests.

An international summary of C export from temperate watersheds in North America, New Zealand, and Russia found a mean of 37.9, median of 18.0, and range of 3.4-417 kg ha^{-1} yr^{-1}, showing that a huge range of export exists in both undisturbed and disturbed (harvested) catchments (Hope *et al*. 1994). A more recent and even broader global review of DOC exports found that in 550 catchments studied, DOC export was as high as 569.5 kg ha^{-1} yr^{-1} (Alvarez-Cobelas *et al*. 2012). This study specifically pointed to soil type as being highly influential of DOC export, finding that organic (wetland) Histosols and mineral Podsols, the two soil types found in the Pockwock watershed, were associated with the highest DOC export.

Researchers have come to different conclusions about the relationship between catchment size and DOC export. Most studies found that stream DOC concentration is inversely related to drainage area (Wolock *et al*. 1997; Alvarez-Cobelas *et al*. 2012), while some others have found the opposite (e.g. Li *et al*. 2015). A variety of potential drivers influence the more commonly found inverse relationship, including that increased sub-surface contact time with DOC-laden water leads to increased decomposition and oxidation of organic C (Wolock *et al*. 1997). While we studied a range of subcatchment sizes within the study area, they are all relatively small (≤385 ha), which could contribute to our results falling on the high end of DOC export compared to similar studies within the region. Environmental factors can be used to predict DOC more accurately for larger catchments than the smaller subcatchments found in the Pockwock watershed (Smith *et al*. 2005).

The proportion of wetland area is often linked to DOC export and yield both in terms of absolute export (Creed *et al*. 2008), and complex interactions with other catchment characteristics (Eimers *et al*. 2008). While our data did demonstrate correlations between the proportion of wetland area and both [DOC] and total annual DOC export, the relatively narrow range of wetland-area proportions of the total subcatchment, from 1.2 to 9.1%, likely masks expression of this relationship within our data. No statistical relationship was found between DOC yield and proportion of wetland area, indicating that other variables may be confounding here, including the previously described effect of amplifying landscape heterogeneity in small subcatchments.

4.4.1.3 Sources of DOC

The relative contribution of different DOM pools to DOC export is an important but still not fully understood component of DOC dynamics. Calibration of DOC export within this study required selection of DOM pools that actively contribute to DOC loads observed in stream samples. This work builds on another integration of CBM-CFS3 into DOC export modelling by Smiley & Trofymow (2017) on Vancouver Island. Their work used only above- and belowground slow pools as C sources to meet observed DOC export, but they recognized the need to possibly include other DOM pools as potential donors for a better understanding of DOC export dynamics.

The selected approach, to consider contributions of all DOM pools substantially in contact with the ground (i.e. omitting only standing snags), is aligned with research indicating that mineral soil is not the only source of exported DOC. Forest floor litter, part of the very fast AG pool, is a known source of DOC-rich leachates (Moore 2003) that may contribute directly to streams and also cause chemical changes in mineral soil that enhance DOC export from soils (Klotzbücher *et al*. 2012). Coarse woody material is a substantial pool of biomass, especially in old-growth forests (Lajtha *et al*. 2005), and in some contexts may contribute more to DOC export than litter (Lajtha and Jones 2018), thus contributing to DOC loading for decades.

The relationship between soil C stocks and DOC export is not straightforward. While mineral soil is a substantial pool of C, evidence indicates that it may reduce DOC concentrations in water moving through it (Yano *et al*. 2005). This is further supported by some findings that DOC export per unit area is inversely related to catchment size (Wolock *et al*. 1997); organic C is decomposed and oxidized in mineral soils and greater contact time further reduces DOC. These results support other research findings that show decreasing DOC in deeper soil horizons (Toosi *et al*. 2014), and a connection between shallower soils, such as those found in our study area, and higher DOC (Gannon *et al*. 2015). However, this relationship is not observed in all studies (e.g. Li *et al*. 2015), and other landscape variables are often found to be more influential.

A variety of research has found that the relative contributions to DOC from different DOM pools vary based on season (Ågren *et al*. 2010; Burrows *et al*. 2013; Wen *et al*. 2020; Zhong *et al*. 2021), management history (Yamashita *et al*. 2011; Lajtha and Jones 2018), and individual high-flow events (Wilson *et al*. 2013), among a variety of other factors. Coarse modelling that operates on an annual timestep such as the present study must consider the possibility of all pools contributing to DOC export. Future research along these lines should consider the individual roles of each pool, though the challenge of integrating a large range of interactions among pools, climate, management history, and landscape characteristics may not yield substantially more useful results.

4.4.1.4 Short-term Harvest Effects

Following timber harvest, increased DOM pools, soil disturbance, and other environmental changes associated with harvesting have been found to contribute to short-term increases in DOC export. Commonly, slash (branches and tree-tops) left on-site contributes to a flush of DOC for a short period of time following harvest (Morris 2009; Webster *et al*. 2022). A wealth of research on boreal forests has linked harvests with higher short-term DOC export, especially where harvests operate within the riparian zone (e.g. Schelker *et al*. 2012), involve site preparation that disturbs soil horizons following harvest (Nieminen 2004; Schelker *et al*. 2012), or take place in drained peatlands (Nieminen *et al*. 2015; Peltomaa *et al*. 2022). Additional research has revealed that temporary reductions in evapotranspiration potential, especially following clearcutting and potentially affected by timing, lead to increased runoff and subsequent mobilization of DOC from DOM pools (Sørensen *et al*. 2009; Wu *et al*. 2014; Webster *et al*. 2022). Compounding increases in export potential following intensive harvests, reduced canopy cover leads to higher soil temperatures that can stimulate microbial activity, producing greater pools of labile C (Schelker *et al*. 2013; Wu *et al*. 2014; Webster *et al*. 2022). Site preparation that disturbs mineral soils can serve to mobilize C both through more hydrologic flow through labile C-rich mineral soils, and increased DOM decay through soil warming (Schelker *et al.* 2013). The combined effect of these impacts is a short-term surge of DOC export following harvests in boreal settings (Kreutzweiser *et al*. 2008). Some but not all these effects may apply to some degree in our study area, particularly changes to runoff and evapotranspiration regimes, increased labile C availability from remnant slash, and increased microbial activity due to elevated soil temperature. Other practices, especially riparian harvesting, operations in drained wetlands, post-harvest site preparation, and the overall intensity of harvests in boreal settings, are not a factor within the Pockwock watershed.

We did not observe a DOC trend in streams draining treatment subcatchments following harvest that was not also present in control subcatchments, indicating that the strong relationship between flow and DOC export is the primary factor in total export. However, the calibrated export model does predict increased DOC export due to spikes in very fast and fast AG/BG pools following harvest (Figure 4.9). That these increases were not observed during the calibration period suggests that increases may not be as significant as predicted, that they are obscured by the natural variation due to precipitation and flow regime, the observed harvests were not sufficiently intensive, or a combination thereof. The lowest-retention harvest applied within the study area during monitoring was within S5S1, where there was 0% retention within a 2.2 ha harvest, representing only 0.9% of the monitored subcatchment (Table 4.2). The highest proportion of harvest treatment was within the small headwater S4S1, where 63.9% of the subcatchment was harvested, but 58% of trees were retained as part of a thinning treatment (Table 4.2). Future efforts to improve DOC export estimates in this region should study immediate stream-water responses to harvest more closely to determine a potential signal that could not be found in our research. This may affect the overall picture of the impact of harvesting on DOC exports to the reservoir.

Understanding relationships between DOC production and the short-term impacts of harvest operations, future management within the study area may consider the importance of mitigating increases to soil temperature and minimizing reductions in potential evapotranspiration. Both objectives can be supported by management practices such as higher-retention harvests that leave mature trees following a harvest to provide shade to cool surface soil and continue to transpire. Partial harvests are now the standard in most of Nova Scotia’s publicly owned forests (McGrath *et al*. 2021). This, in addition to other practices already in use in the study area such as riparian exclusion zones and abstaining from site preparation, will likely minimize DOC export. On the other hand, slash loading contributes to DOC export, but retaining slash on site is important to support nutrient availability and biodiversity (McGrath *et al*. 2021). While slash removal may reduce DOC exports, it is not nutrient-sustainable in the relatively coarse-textured, acidic soils found in the study area (Keys and Bockstette 2023) and therefore will not likely be adopted.

4.4.2 Simulation Results

4.4.2.1 Effects of Forest Timber Management

The long-term consequence of management is a steady reduction in DOM pools and corollary decrease in DOC export. Mineral soil C is the most abundant DOM pool and gradual reductions are predicted in all harvest-inclusive scenarios (Figure 4.9). Modelled total DOC export and respiration losses followed the same trend (Figure 4.9) and in the long term, all pools respire less C in harvest scenarios versus the no-harvest management regime. Additionally, management intensity was inversely linked to respiration, and therefore also to DOC export (Figure 4.12). These results compare favourably to longitudinal studies of the impacts of harvesting on DOC export.

Yamashita *et al*. (2011) found unequivocally that DOC export had been reduced 30 years after clearcutting in a North Carolinian forest compared to a reference site. Another study in New Hampshire found that harvesting could lead to a reduction in DOC export, although the effects of landscape characteristics, especially presence of wetlands, were more influential in DOC export dynamics (Cawley *et al*. 2014). Research in a SE Vancouver Island watershed that used CBM-CFS3 to model hydrologic C export from actual and alternative historic land management scenarios similarly estimated that harvest compared to no-harvest simulations had reduced DOC exports over the long term (Smiley and Trofymow 2017). These types of results are supported by Lajtha and Jones (2018) whose work in Oregon found that the biomass of coarse woody material, especially associated with old-growth forests, is linked to greater DOC export and is a previously underestimated contributor to DOC. They specifically linked younger forests to lower DOC exports.

Not all long-term studies find a clear and unequivocal reduction in DOC exports following harvests. Some have indicated that harvests lead to an initial increase of DOC export followed by a return to pre-harvest or lower values (Morris 2009; Glaz *et al*. 2015). In some cases, environmental factors such as the type and distribution of soil types overshadow the effects of harvest regimes (Hope *et al*. 1994). Other research has found no relationship between DOC export and forest management, instead indicating a stronger relationship with catchment area (Hancock *et al*. 2022). These results, however, are less comparable to our own due to relative catchment size, much lower DOC, and a difference in DOC export calculation methods that minimizes the importance of peak flows on DOC export.

4.4.2.2 Climate Effects

Our findings show that climate change exerts less control on DOC export compared to effects of forest timber management. However, the selected models may underemphasize the importance of changing temperature and precipitation regime to predicting future export regimes. Increases in air temperature are generally correlated with higher microbial activity and increased labile C production for potential export (Wen *et al*. 2020). Laudon *et al*. (2012) determined that the positive relationship between MAT and DOC export should yield a fairly predictable DOC export response under a changing climate.

Many precipitation related factors exert some degree of control over DOC export including total annual precipitation, timing and intensity of precipitation and associated runoff (especially where snowpack is concerned), and moisture conditions between precipitation events (Wilson *et al*. 2013). That air temperature and discharge are key individual controls on C export is well supported in the literature (Raymond and Saiers 2010; Wallin *et al*. 2015); however, the interactions of precipitation and temperature regimes also produce more complex results. DOC export is highly seasonal in both boreal and temperate forests (Ågren *et al*. 2007), with spring snowmelt exporting a large quantity of DOC (Raymond and Saiers 2010). Winter climate can also explain a large amount of variability in spring DOC export (Ågren *et al*. 2010), although some studies have found that winter snowpack and overall climate have minimal effects on DOC export (Hentschel *et al*. 2009; Kasurinen *et al*. 2016). Changes to temperature and precipitation regimes that may render winters warmer and wetter may also produce greater DOC export year round, or produce other unexpected results.

CBM-CFS3 uses MAT to determine decomposition rates (Kurz *et al*. 2009), and therefore temperature influences repiratory losses and transfers to the slow C pools, and decomposition of the slow C pools provides the source of exportable DOC. CBM-CFS3 does not consider moisture conditions, including winter snowpack. While calibrated hydrologic models for the watershed can use climate scenario data to simulate future runoff, snowpack, and other hydrologic movement and storage, it does not feed these results back into CBM-CFS3. Therefore, intra-annual DOC export patterns are not modelled and the effect of a changing climate, especially milder winters, may produce unexpected changes. Barring drastic changes to the system's behaviour, a preponderance of research supports our findings that landscape characteristics (e.g. soils, forest cover, wetland area, hydrology) and management regime are more closely correlated with differences in DOC export than climate variables (Pastor *et al*. 2003; Raymond and Oh 2007; Zhong *et al*. 2021).

The effect of climate change on forest dynamics was not considered in this research. Climate-induced changes in tree ranges, growth pattern due to longer growing seasons, success under different moisture regimes, the spread of pests, the changing frequency and intensity of natural disturbances and other complex interactions are not incorporated in the selected methods. These variations will cause changes in forest growth and mortality, and require interventions to manage the accumulation of dead organic matter and potential for DOC export in the Pockwock watershed. Future investigation of the potential future of C dynamics in the study area should examine the role of changing climate on forests to determine whether it might have an appreciable effect on the C inputs to the system such that it too may impact future DOC loading in Pockwock Lake.

4.4.2.3 Future DOC Regime in the Pockwock Watershed

To build on Wen *et al*.'s (2020) concept of DOC export controls, management regulates supply, temperature controls production, and hydrology regulates export. The future of DOC loading in Pockwock Lake will depend on a combination of how the forest is managed, the future temperature regime, and both annual and event-scale changes in precipitation. Pockwock lake [DOC] is currently trending upwards. Pointing to reduced sulphate deposition as a key factor in increasing DOC export (Evans *et al*. 2006; Hruška *et al*. 2009), some researchers have suggested that a levelling-off of these impacts may cause DOC export to hit a natural ceiling (Monteith *et al*. 2007; Evans *et al*. 2012). However, this history of acid rain may have reduced soil buffering capacity to the point where we may see continued DOC export increase for some time into the future (Lawrence and Roy 2021). We calibrated the DOC export model using current conditions and these findings do not include accounting for future chemical deposition scenarios or shifting conditions resulting from ongoing soil chemistry recovery processes.

Though not the focus of this study, the role of wetlands on total DOC export cannot be excluded from discussion on the future of DOC loading in Pockwock Lake. Calibration of the DOC export model found that the 4.8% of the study catchments classified as wet areas were responsible for over 60% of the total DOC export (Table 4.6). The future of wetlands as C sources or sinks depends on a complex relationship between changing temperatures and precipitation, in which slight variations between future climate scenarios could see wetlands shift to one or the other (Salimi *et al*. 2021). While the ability to manage these significant DOC sources is limited, it may be worth considering what options are available to influence whether they store or supply C to source waters.

4.5 Conclusion

Through an integrated modelling strategy, we predict that different levels of timber harvesting will variably reduce DOM pools over the long term, thus reducing respiratory losses from organic matter decomposition. Using CBM-CFS3 to quantify respiratory losses under a variety of management regimes, we examined the full suite of DOM pools alone or in combination calibrate a DOC export model against observed DOC exports for a 1,200 ha study area over a four to five-year monitoring period, finding it feasible that all DOM pools export a portion of labile C via hydrologic flow. However, it appears that using all ground C pools versus only slow C pools had little effect in the overall calibration and predicted total DOC export, though it influenced the proportion of labile C exported hydrologically versus through respiratory losses. Examining the effects of both forest timber management regimes and climate change scenarios on future DOC export, we found that management has a greater overall effect, though the role of climate has many uncertainties associated not only with temperature or precipitation regime change, but also in the complex interactions between both. The trends uncovered in this research should inform future management efforts to protect the treatability of water drawn from Pockwock Lake.

Most fundamentally, timber harvesting in the Pockwock watershed is expected to reduce DOC loading over the mid to long term. Even low-intensity forest harvest may be able to arrest DOC export increases from uplands as compared to a no-harvest regime. Increasing intensity of forest timber management activities causes additional reductions in DOC export. However, the goal of reducing DOC export must be balanced against other measures of forest ecosystem sustainability, environmental health, water quality, and water treatability. Watershed managers will need to decide how to balance these metrics to ensure a sustainable, easily treatable water supply into the future that is supported by a healthy forest.

Chapter 4 References

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5 Discussion & Conclusion

Chapters 2 through 4 provide conclusions specific to the purpose of each chapter, but in this chapter, I will provide higher-level discussion and conclusions that address the outcomes for managers and other researchers. The focus of these conclusions is applicability for managers of forested water supplies. This includes the Pockwock watershed, as the subject of the current research, but also considerations for applicability elsewhere. Additional interpretation of the results in a research context highlights opportunities for future work that emerged through this study, and key considerations for the generalizability of my findings to other landscapes.

5.1 Findings for Management

Chapters 2, 3, and 4 build on one another, forming the conceptual and mechanistic foundation for addressing the guiding research questions. The three research objectives are ultimately met in Chapter 4 when the forest growth and disturbance modelling, C dynamics, and hydrologic models are used in concert to estimate DOC export under different management regimes and climate scenarios. I will not restate the conclusions of each chapter; rather, I will summarize how each of the three hypotheses was addressed in Chapter 4, in preparation for a broader discussion of the implications of these findings.

- **Hypothesis 1**: Timber harvests, as practiced in the Pockwock watershed, will not cause any immediately appreciable changes in DOC, but by reducing DOM accumulation over the long term, we project an inverse relationship between timber harvest intensity and DOC exports.

Through the observation period of 2018-2022, I monitored DOC export in five subcatchments, three of which were harvested during this period. No anomalous trends were detected in DOC export where timber harvests and associated activities took place (Figure 4.5). This supports the hypothesis but is contrary to some literature suggesting that short-term DOC export increases following harvests. Key differences between the timber harvests in the Pockwock watershed and in past studies are the degree of soil disturbance, proximity of work to streams, and prevalence of activities in wetlands. However, simulation modelling did forecast an inverse relationship between harvest intensity (here, an indication of the frequency of harvest) and long-term DOC export regime, further supporting the hypothesis. These findings corroborate other literature that draws a clear connection between the diversion of biomass from DOM pools via harvest and mid- to long-term reductions in labile C production (Cox *et al*. 2024). This suggests that some degree of timber harvesting will reduce DOC inputs to Pockwock Lake, contributing to improving water treatability.

Removing merchantable volume, minimizing overall disturbances, and keeping forests younger and growing more vigorously reduces C inputs to the soil and reduces it over time. These impacts are clearly visible through modelling within a decade of management (Figure 3.10) and produce the lowest DOC export within four to five decades of initiating the more intense management regime (Figure 4.13). My results also suggest that reducing the average age of the trees in the forest is a contributor to reducing DOC export.

> **Hypothesis 2**: More severe climate scenarios will correlate with higher DOC export predictions from the integrated model framework.

Results from simulation modelling demonstrated that climate does appear to have an impact on DOC export, as corroborated in the literature (Figure 4.13). However, the directionality of this trend is not as consistent as the effect of timber harvesting. Climate can influence the model framework at two key points. The first is mobilization from DOM pools where warmer temperatures increase decay rate and provide more labile C for hydrologic export. At the hydrologic export stage, both total volume and timing of precipitation can influence DOC export. With average annual precipitation in the region not expected to change drastically but most climate scenarios pointing to more variability, we should expect more extreme dry and wet years (Figure 4.3). Combined with increasing PET, the potential for low DOC export during dry years is likely to counterbalance the higher DOC export during wet years. However, the simulation results do not demonstrate that this is consistently a net increase or reduction of annual DOC export, nor does it seem to greatly increase intra-decadal variation in DOC export over a baseline climate scenario.

> **Hypothesis 3**: Reductions of DOM caused by timber harvesting and corresponding decreases in DOC export will mitigate some but not all DOC export increases caused by changing temperature and precipitation regime of climate change scenarios.

Contrary to expectations, timber harvests produced a much clearer, more consistent, and more dramatic change in DOC exports over the simulation period versus the effects of climate (Figure 4.13). Examining a management regime in which the entire study area was treated with routine, planned timber harvests, climate's influence on DOC export was almost negligible when compared to the effect of harvests. Although there is a trend towards the highest DOC export under the warmest climate scenarios (Figure 4.12), when examined more closely the pattern of DOC export diverges under different climate scenarios (Figure 4.13).

5.1.1 Future Forest Contributions to DOC Loading

Predictions from simulation modelling are clear – portions of the forest managed through planned timber harvesting will export less DOC over time than similar portions without such management interventions. The inverse relationship between DOC export and harvest intensity may suggest on its own that harvests should be maximized to improve water quality, but this relationship likely has limits, and in a modern forest management context, there must be a balance between managing for DOC with other metrics of water quality and ecosystem integrity. Management in the Pockwock watershed can strike this balance through application of partial harvests that create multi-aged stands. The shade provided by retained canopy following partial harvests maintains higher PET, which has been found to contribute to lower DOC export (Raymond and Oh 2007) and minimizes increases to soil temperatures that would increase decay rates (Hashimoto and Suzuki 2004). Additionally, the physical interception of rainwater and retention of live root systems mitigate the risk of soil erosion (Blanco-Canqui and Lal 2008). However, management intensity correlates with DOC export because removing mature trees prevents stem biomass from becoming DOM – can partial harvests offer the same benefits as the clearcuts that were modelled in Chapter 4?

Clearcuts were modelled due to their spatial simplicity and limitations of the forest growth and disturbance model. Looking further back to Chapter 3, alternative harvest management approaches were examined and how they affect DOM accumulation and losses to the atmosphere (Figure 3.6; Figure 3.7). Recalling that DOC export is calculated as a fraction of labile C respired to the atmosphere, cumulative atmospheric losses, while not predicting DOC export directly, are a good proxy for potential DOC export trends. Here, high-retention gap irregular shelterwood was found to produce fewer atmospheric C losses than clearcutting every 100 years. The high-retention gap irregular shelterwood system is a method of producing multi-aged canopies in areas where there is a high windthrow hazard and patch stand structure (McGrath *et al*. 2021: 41), thus well suited to the shallow soils and exposed slopes of the Pockwock watershed. While this timber harvest method may not reduce DOC exports as much as frequent clearcuts, when considering other benefits to soil retention and ecological integrity, high-retention gap irregular shelterwood and other similar partial harvest methods may offer the greatest benefits overall in the Pockwock watershed.

5.1.2 Proactive Management

Forests are naturally dynamic, experiencing continual tree mortality from causes both routine and catastrophic, including self-thinning with age and severe natural disturbances such as fire or hurricanes. These most-severe disturbances are likely to increase in both intensity and frequency with climate change (Myers and van Lear 1998; NOAA 2024), and represent an increased threat to the water supply. Fire is linked to increased DOC export (Emelko *et al*. 2011), exposes soil to additional effects that cause C loss, and is very likely to increase in frequency and severity because of climate change in this region (Taylor and MacLean 2024). Hurricanes cause root tip-ups that disturb soils, possibly increasing DOC (and other C) export in the short term similar to intentional soil disturbance as part of site preparation, causing both more direct hydrologic access to labile C and increased DOM decay from warmer soil conditions (Piirainen *et al*. 2007; Schelker *et al.* 2013). Insect disturbances, already on the rise due to introduced pests, may continue to gain prominence as a natural disturbance agent with changing climate and further introductions of non-native pests, causing standing tree mortality and increasing fuel load for potential forest fires. These disturbances can all cause increases in DOC export, but proactive management may provide relief to their frequency, severity, or both. Planned harvests can reduce fire fuel loading by managing species composition and age distribution, reduce windthrow risk by removing vulnerable, older trees, and remove trees ahead of a species-specific pest (e.g. spruce budworm). This both directly mitigates possible excess DOC export and requires fewer reactive measures such as salvage harvesting following windthrow, fire, or insect disturbance. Additionally, proactive fire management may reduce firefighting efforts in the event of a fire start including activities that could affect water quality depending on the equipment and chemicals used, and the scope of the effort.

The forests within the provincially protected Pockwock Wilderness Area (PWA) are not eligible for timber harvests except in response to natural disasters for the purpose of preventing further hazards to water quality (Nova Scotia Environment 2017). This is in contrast to the remainder of the watershed, which, while subject to the special management practices of the Pockwock Lake Watershed Protected Water Area (Province of Nova Scotia 1994), is nonetheless eligible for timber harvests except where other regulations prohibit (e.g. riparian special management zones). DOM accumulation for these two areas was modelled separately in Chapter 3 (Figure 3.10) demonstrating that areas regularly subjected to planned harvests see a decrease in stored DOM, unlike areas where planned harvests are prohibited and DOM increases. Unfortunately, it is not possible to separate the DOC contributions of the PWA versus the rest of the watershed in any single monitored subcatchment, and a comparison of DOC exports from the two land areas in Chapter 4 was not possible. However, we can glean from the findings in Chapter 3 and the inverse relationship between management intensity and DOC export (Figure 4.12) that the PWA is likely to yield a greater amount of DOC per unit area to Pockwock Lake than the remainder of the watershed as the consequences of differing management regimes are realized over future decades.

5.1.3 Additional Considerations

There are aspects of this research that managers should consider when interpreting the results including scalability, in-stream processes, and balancing water treatability with other environmental goals. First, these results are based on the study of subcatchments that drain approximately 35% of the Pockwock watershed's land area. The remaining land area is either downstream of the monitored points, in the main unmonitored Lacey River catchment (1,730 ha, 41% of watershed land area), or in small catchments that drain directly to the lake. Within the Lacey River catchment are land uses not observed within the monitored portion such as utility (highway and powerline) corridors and urban development. The pattern of results discussed herein are based on a diverse range of forest conditions for this watershed and should extrapolate to the whole watershed. However, whether the strength of the relationship between timber harvests and DOC export would be the same is unknown.

Wetlands were included in the study area and their contribution to total DOC export determined through calibration. In the most likely DOM pool C contribution scenario (Table 4.6) wetlands are expected to contribute 64% of DOC, while only comprising approximately 5% of the land area. This high proportion of total loading is corroborated in the literature (Creed *et al*. 2003), but the future of these wetlands is less certain. Changes in precipitation patterns may lead to wetlands drying (or experiencing more, longer dry periods followed by flooding), increased temperatures could accelerate photosynthesis, and a variety of other possible changes could affect the amount and pattern of DOC exports from the watershed's wetlands (Salimi *et al*. 2021). Due to their outsized impact, small perturbations here could cause increases in DOC that surpass any gains made through upland forest timber management. Alternatively, reductions in wetland DOC exports are possible. Neither scenario minimizes the importance of any steps that can be taken upland to reduce total DOC export.

While the relationship between upland and wetland conditions has been established at the specified monitoring points, this study does not examine the role of in-stream and in-lake processes that affect DOC levels. Various means of DOC degradation and autochthonous production can affect concentration and quality of DOC and ultimately influence water treatment requirements (Orlova *et al*. 2024). DOC concentrations in Pockwock Lake water between 2017 and 2023 averaged 3.4 mg L^{-1} (Halifax Water, unpublished data), substantially lower than the average 19.8 mg L^{-1} observed in streams during the monitoring period. It is not clear how a changing climate will affect these dynamics as some researchers have linked increased temperatures with suppression of in-lake autochthonous DOC accumulation, but production via algal blooms may be an increased threat in warmer, more nutrient-rich waters (Zhou *et al*. 2018). Ultimately, as with wetland-derived DOC, the direction and relative influence of aquatic processes on DOC is not known, but this does not diminish the importance of managing the land to affect the most positive outcome for water treatability.

Despite watershed managers' search for management techniques to minimize DOC in the water supply, they will ultimately need to balance DOC reductions against other values. Alternative goals that may not align with efforts to lower DOC are numerous, key among them including retaining old growth forest, providing species habitat, minimizing water turbidity, avoiding landscape discontinuity by road networks, and much more. It would be wrong to think of the Pockwock watershed as a single-purpose watershed, and accordingly, it must be managed for more than easily treatable water. A wide range of forest management regimes are compatible with a multi-purpose watershed, including timber harvesting. At the time of its establishment in the 1970s as a water supply, the

Pockwock watershed was no stranger to management for timber supply, yet it was suitable as a high-quality source for HRM's future water needs. However, whereas DOC export is linked to older, untreated stands, this relatively new consideration for water supply managers raises questions about the compatibility of different management objectives. It is up to watershed managers and others with a say in management regimes to decide the balance of priorities, if gains in water treatability can be balanced with, or are outweighed by, other measures of environmental quality.

5.2 Key Research Takeaways

The primary takeaway and contribution of this research to the literature is expanding upon relationships between DOC export, forest management, and climate change. Past research has demonstrated, primarily through longitudinal studies, variable DOC outcomes immediately following timber harvesting and typically finding long-term reductions in DOC export following harvesting. Additionally, researchers have found that while the relationship between climate and labile C production and hydrologic export is complex, DOC export is generally favoured with higher temperatures and more erratic precipitation patterns. A key question coming into this study was whether DOC export reductions from management of upland forests would be able to counteract probable increases due to climate change. While I hypothesized that climate would be too great an influence to counteract, the results do not support this, and the research suggests that timber harvesting may be a critical management tool for mitigating increasing DOC exports in the long term.

5.2.1 Future Research

This novel attempt to predict the potential effects of management regime and future climate on DOC exports has the potential to influence management in the Pockwock watershed and other source water supplies where rising DOC is a concern for water treatment now or in the future. However, this work has also highlighted important lessons for future research and some knowledge gaps that remain for further study.

The outsized impact of wetlands on DOC export and uncertainty about their future contributions under a changing climate deserve more attention, including regional studies that consider the temperate, maritime climate of this study area. If increasingly variable precipitation patterns lead to wetland drying followed by years of heavy flushing, this could have significant consequences for lake DOC and subsequent treatment.

Further research is required into the C dynamics of Pockwock's wetlands to understand the current volume of DOC contributions from this source, how various impacts of climate change will affect future DOC exports from wetlands, and if there are management actions that might help ensure that DOC exports from wetlands do not increase over time.

Similarly, there is great uncertainty about the future of DOC exports as a regional matter. Historic increases, likely caused by a combination of decreasing acidic depositions and a changing climate, have caused issues for water treatment from surface waters such as Pockwock Lake. Will reduced, stabilized acidic depositions cause a return to a stable pre-industrial DOC export regime, as predicted by Monteith *et al.*(2007), or will changing climate and depleted soil cations continue to increase DOC exports ever further?

While the process of conducting this research uncovered critical uncertainties that require further examination, it also utilized three key techniques that, based on their successful implementation here, should be considered for future modelling efforts. These included integration in modelling scenarios of natural disturbance regime and associated management interventions, assessing the use of partial harvests in managing for DOC, and integrating hydrologic DOC export into carbon budget modelling.

Natural disturbance modelling is employed to varying levels of complexity depending on the type of model and the purpose of the exercise. Timber supply modelling, for example, uses more simplistic assumptions about disturbances than process models that can account not only for the impacts of disturbances on stocks, but also consider disturbance relationships such as blowdowns increasing the likelihood of fire (Seidl *et al*. 2011). This research considered not only natural disturbances, but the effects of post-disturbance interventions on changes in forest C pools. Stands suffering blowdowns or insect mortality were salvage-harvested in some model runs and the differences between regimes compared to determine the effects of such interventions on DOM pools (Figure 3.10). While this implementation used a relatively simple approach and had key limitations largely arising from the semi-distributed nature of the forest model, it accomplished the goal of accounting for C removed from the watershed through salvage harvests following disturbances. This had a notable effect on DOM accumulation (Figure 3.10), especially in protected areas where salvage harvesting was the only type of harvesting employed in most management regimes. Given that management in a water supply watershed with DOC loading problems is more likely to be practiced in a manner sensitive to excess DOM accumulation, the possibility of salvage harvesting should be incorporated in modelling. While these considerations are not novel in forest modelling, they proved important to understanding the full picture of watershed C dynamics and accounting for potential DOC export.

A preponderance of research examines the effects of clearcuts on DOC exports, largely due to the dominance of clearcutting in boreal settings (Girona *et al.* 2023) where most DOC research is carried out. The present research, however, considered partial harvests and found that it may balance the DOC mitigating benefits of harvest with the environmental impacts of clearcutting. While the modelled implementation of partial harvests was relatively simplistic due to forest model design, it was effective at determining biomass removals via harvesting, effects on different DOM pools, and establishing a multi-aged canopy (Figure 3.6). This is a first step in addressing a stated need within the literature for more research into the potential of partial harvests to mitigate impacts to water quality (Nieminen *et al*. 2017). This modelling approach should be followed up by further observational study of the outcomes of partial harvesting. What limited research has attempted to address this to date (Lockaby *et al*. 2004) has not made firm assertions about the link between partial harvests and DOC dynamics. While the outcomes of biomass removals on C budgets are straightforward, the effects of canopy retention on soil C processes (decay rate, moisture regime), PET, and hydrologic export are less clear on their own and in concert. Research in forested Finnish peatlands found that peat released less CO_2 in the short term following partial harvests versus clearcuts (Korkiakoski *et al*. 2023). The observed differences in post-harvest C emissions were largely attributed to increased decay due to warmer soil (from reduced canopy) and higher water table level in the clearcut, further facilitating labile C production. While peatlands are hardly representative of the shallow mineral soils of the Pockwock watershed study area, these biophysical impacts are similar to those observed in mineral soils and further study should examine whether the relationships hold in areas like the Pockwock watershed.

Integration of CBM-CFS3 with a hydrologic model and DOC loading calibration to estimate DOC export was a success and provided valuable insights into the consequences of both management and climate change on DOC. Hydrologically exported C came from labile C that CBM-CFS3 assumed to be lost through respiration, the only mechanism of C loss in the model (Kurz *et al*. 2009). This is not the first research to use CBM-CFS3 to understand hydrologic export of C (Smiley and Trofymow 2017), nor is it the first to say that hydrologic C export represents a major gap in current C budgeting that requires further consideration. Where water is responsible for exporting a substantial amount of labile C, such as in the Pockwock watershed, failing to account for this loss could lead to overestimation of soil carbon. In the Pockwock watershed, this accounted for at least 1.5% of total C exports, while Hararuk *et al*. (2022) found that this overestimation could be in the range of 1-5% in the United States. In the case of the application of CBM-CFS3 in this research, it is unclear whether the model's estimates of total C lost (respired and hydrologic losses) are accurate and 1.5% is actually lost hydrologically, or whether the 1.5% is an additional, unaccounted loss of C from the system. In the former case, this has implications for CBM-CFS3's use as a carbon budgeting tool, whereas it may be overestimating respired C from forests. In the latter case, it raises more substantial questions about where the additional C loss is coming from, and how such systems change over the long term.

Understanding and accounting for this process is critical in a changing climate, as modelling future system behaviour will not necessarily be able to depend on long-studied and well established relationships. Following clearcuts, PET is greatly reduced which leads to greater runoff, and has been linked to greater DOC exports. Without integrating the resulting increased hydrologic export, C dynamics models will likely overestimate DOM pools. This effect was noted in Great Britain, where Williamson *et al*. (2023) calculated an increase in DOC exports due to the prevalence of plantation management. This increase, approximately 0.168 Tg yr^{-1} of C, represents 15% of current net annual CO_2 capture by British forests, and is not considered in current C budgeting, what the authors rightly refer to as a "leak in the system". Integrating hydrologic export into C budget modelling requires including hydrologists in the design of C budget models. Forest hydrologists who understand how water moves through the forest floor and soils and the functions it performs along the path downstream must be involved in designing and refining models like CBM-CFS3. Without integrating this critical pathway, C budgeting will always have a leak in the system that results in an overestimation of soil carbon and lack of consideration for the downstream effects of management decisions.

5.2.2 Generalizability

In addition to the qualifications to applicability discussed above, there are two conditions for interpreting these results, both of which are fundamental to how these results are understood in other contexts. First, insofar as these results suggest a course of action for management, they only apply where [DOC] is problematic. This may not be limited to source water supplies, as the literature has demonstrated that excess DOC loading (typically from acute and local anthropogenic causes) can contribute to environmental issues. Almost universally, C storage will be favoured for its contributions to mitigating climate change versus the potential for reducing DOC export, if it is even considered. This may change if globally increasing DOC causes some systems to hit limits of natural function, but the long-term nature of mitigating DOC export, and the whole-watershed approach required, makes management for this goal unlikely.

The second condition for interpreting these results in other settings is the environmental context in which these results were obtained. The study area's temperate climate, relatively high precipitation, and the unique ownership structure of the water supply may limit the applicability of these results in other settings. The timing and phase of precipitation, in addition to a relatively low snowpack may have been influential in the relatively low degree of influence that climate had on DOC when compared to management. Climatic changes in boreal regions, for example, may have a more pronounced effect on DOC export due to changing snowpack and spring freshet regime, surpassing tipping points for precipitation phase, or otherwise.

In the Pockwock watershed, Halifax Water has a recognized and respected stake in the forest, able to influence management decisions in over 85% of the watershed's land area. This stake includes the PWA where, despite a prohibition on proactive forestry interventions, the utility may apply for a license to carry out management measures to mitigate acute threats to water quality. In Chapter 3, DOM reductions in proactively managed portions of the watershed (~48% of total land area) were offset by DOM increases in the portion not subject to planned forestry interventions (~39% of the total land area, Figure 3.10). The difference in DOC export outcomes was quite pronounced between managing what is legally eligible for harvest versus proactively managing the entire forest area (Figure 4.12). Where water authorities have influence over less of the management regime of the total watershed area, it may not be possible to realize the kinds of DOC export reductions predicted by this modelling. However, the inability to manage the entire landscape to minimize DOC exports does not diminish the importance of making progress where proactive management is possible. Water treatability improvements will be realized over long timescales and efforts now are important to see impacts even decades in the future.

5.3 Conclusion

The United Nations in 2010 recognized access to safe, clean, accessible, and affordable drinking water as a human right (United Nations 2010). While the resolution's text made it clear that the General Assembly was primarily focused on the more than 12% of the global population lacking access to safe drinking water, the importance of maintaining existing water supplies is implicit. Residents of HRM have long enjoyed safe, clean, and affordable water access, but as the water quality in our surface reservoirs changes, this is increasingly because of the water treatment technologies, resources, and skills employed at source water supply plants. Still, changes to water quality are testing the limits of current treatment capacity and requiring investments to keep up with these changes. Geosmin, produced by algal activity and first detected in Pockwock Lake in 2012, continues to produce benign but noticeable odour in drinking water. Addressing this challenge will take several years and require multi-million dollar water supply plant upgrades (Halifax Water 2024). Similarly, increasing DOC requires greater removal capacity. Citizens of HRM are fortunate that these kinds of water treatment challenges are surmountable with available resources, and given the importance of safe drinking water, appropriate investments will be made to this end. However, it may be more affordable and sustainable in the long term to mitigate these risks through proactive forest management, a task that is increasingly challenging in a multifunctional watershed.

Forests provide high-quality water – variations of this relationship are idiomatic in discussions about surface water supplies. The nuance missing from that assertion is how the forest is managed, and many would purport that one method is the 'right way' versus others. On the extreme ends of the management spectrum are preservation and total exploitation – from taking a hands-off approach to prioritizing timber harvests ahead of all else. There are proponents and examples of each if we look beyond our region, but in Nova Scotia more moderate management tends to dominate through partial harvest techniques over clearcuts and recognition of the importance of and support for non-timber forest values. This is the case in the Pockwock watershed where harvesting is already practiced – where possible – to promote easily treatable water, mitigate the risk of future disturbances that threaten the water supply, and support a broad suite of forest values. Mitigating future DOC loading is just another consideration for the watershed's forest managers when planning future interventions.

The Pockwock watershed has served an increasing number of purposes to humans over time. For thousands of years, the watershed and its surrounding environs were overwintering land for the Mi'kmaq until 18th century European settlement, when land grants made it a source of timber and economic prosperity for the area. Eventually, it became home to burgeoning communities like Hammonds Plains and then a municipal water supply to the region's largest urban area. The late 20th century saw the addition of a major provincial highway and power transmission lines to the watershed's eastern extent, and finally the establishment of the Pockwock Wilderness Area in the 2010s bound management of approximately 39% of the watershed's land area by strict conservation rules. This is a truly multifunctional watershed. We can either continue to demand this full range of uses for the watershed, understanding that doing so will come at a cost especially for water treatment, or reevaluate the suite of demands that we place on this unique area.

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Appendices

Appendix 1: CBM-CFS3 Disturbance Matrices

Disturbance matrices below are either based on or modified from CBM-CFS3 defaults (Kull *et al*. 2011). Modifications were made to several to either represent extreme scenarios (e.g. 100% clearcut) or to use existing disturbance matrices as the basis for a different, hypothetical disturbance type (e.g. complete wind blowdown followed by salvage, based on more generic disturbance types). See Kurz *et al.* 2008 for pool definitions, and definitions of model turnover, transfer and other parameters.

Growth Year

	Carbon from: (in order of operations)		
Receiving Pool:	**Biomass Turnover**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	Merch & Bark (@0.0067)		
Branchsnag	Other (25% @0.04)		
VFastAG	Foliage (@0.95 OR 0.15 HW/SW) Fine (50% @ 0.641)		
Fast AG	Branchsnag (@0.10) Coarse (50% @ 0.02) Other (75% @ 0.04)		
Medium	Stemsnag (@0.032)		
SlowAG		Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	Fine (50% @ 0.641)		
FastBG	Coarse (50% @ 0.02)		
SlowBG		VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

Harvest 100% clearcut

	Carbon from: (in order of operations)		
Receiving Pool:	**Harvest Transfers**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	Stemsnag (0%)		
Branchsnag	Branchsnag (0%)		
VFastAG	Foliage (100%) Fine (50%) VFastAG (100%)		
FastAG	Coarse (50%) Branchsnag (100%) Other (100%) FastAG (100%)		
Medium	Stemsnag (100%) Merch (0%)* Medium (100%)		
SlowAG	SlowAG (100%)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	Fine (50%) VFastBG (100%)		
FastBG	Coarse (50%) FastBG (100%)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

*In CC < 100%, a portion of merch goes to Medium

Fire

	Carbon from: (in order of operations)		
Receiving Pool:	**Fire Transfers**	**Decay (P_t)**	**Physical Transfer**
VFastAG	VFastAG (0.04922) Foliage (SW 0.014902, HW 0.011191) Fine (0.33023)		
FastAG	FastAG (0.407503) Branchsnag (100%) Coarse (0.5)		
Medium	Medium (0.853235) Stemsnag (100%)		
SlowAG	SlowAG (0.675951)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	VFastBG (100%) Fine (0.5)		
FastBG	FastBG (100%) Coarse (0.5)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)
Stemsnag	Merch & Bark (100%)		
Branchsnag	Other (SW 0.807299, HW 0.94558)		

Transfer to	**From**
Atm Gas	Other (SW 0.192701, HW 0.05442) Foliage (SW 0.985098, HW 0.988809) Fine (SW 0.66977, HW 0.611574) VFastAG (0.95078) FastAG (0.892497) SlowAG (0.324049) Medium (0.146765)

Wind (total blowdown)

	Carbon from: (in order of operations)		
Receiving Pool:	**Wind Transfers**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	Merch & Bark (15%)		
Branchsnag	Other (15%)		
VFastAG	VFastAG (100%) Fine (50%) Foliage (100%)		
FastAG	Branchsnag (100%)* FastAG (100%) Coarse (50%) Other (85%)		
Medium	Stemsnag (100%)* Medium (100%) Merch & Bark (85%)		
SlowAG	SlowAG (100%)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	VFastBG (100%) Fine (50%)		
FastBG	FastBG (100%) Coarse (50%)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

* Stem and branch snag transfers to medium and FastAG (respectively) happen before transfers to stem/branch snag from merch/other to simulate fragile, rotting, standing material being blown down in wind

Insect (total loss)

	Carbon from: (in order of operations)		
Receiving Pool:	**Insect Transfers**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	Stemsnag (100%) Merch & Bark (100%)		
Branchsnag	Branchsnag (100%) Other (100%)		
VFastAG	VFastAG (100%) Fine (50%) Foliage (90%)*		
FastAG	FastAG (100%) Coarse (50%)		
Medium	Medium (100%)		
SlowAG	SlowAG (100%)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	VFastBG (100%) Fine (50%)		
FastBG	FastBG (100%) Coarse (50%)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

* Remaining 10% of foliage goes to gas

Harvest 40% CT

	Carbon from: (in order of operations)		
Receiving Pool:	**Harvest Transfers**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	Stemsnag (60%)		
Branchsnag	Branchsnag (60%)		
VFastAG	Foliage (40%) Fine (20%) VFastAG (100%)		
FastAG	Coarse (20%) Branchsnag (40%) Other (40%) FastAG (100%)		
Medium	Stemsnag (40%) Merch (6%)* Medium (100%)		
SlowAG	SlowAG (100%)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	Fine (20%) VFastBG (100%)		
FastBG	Coarse (20%) FastBG (100%)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

*Based on 15% Merch → Medium in CC, multiplied by 40% removal

Insect & salvage (total loss followed by salvage harvest)

	Carbon from: (in order of operations)		
Receiving Pool:	**Insect Transfers**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	Stemsnag (100%) Merch & Bark (15%)		
Branchsnag	Branchsnag (100%) Other (100%)		
VFastAG	VFastAG (100%) Fine (50%) Foliage (90%)*		
FastAG	FastAG (100%) Coarse (50%)		
Medium	Medium (100%)		
SlowAG	SlowAG (100%)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	VFastBG (100%) Fine (50%)		
FastBG	FastBG (100%) Coarse (50%)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

* Remaining 10% of foliage goes to gas; remaining 85% of merch goes to Product

Wind & salvage (total blowdown followed by salvage harvest)

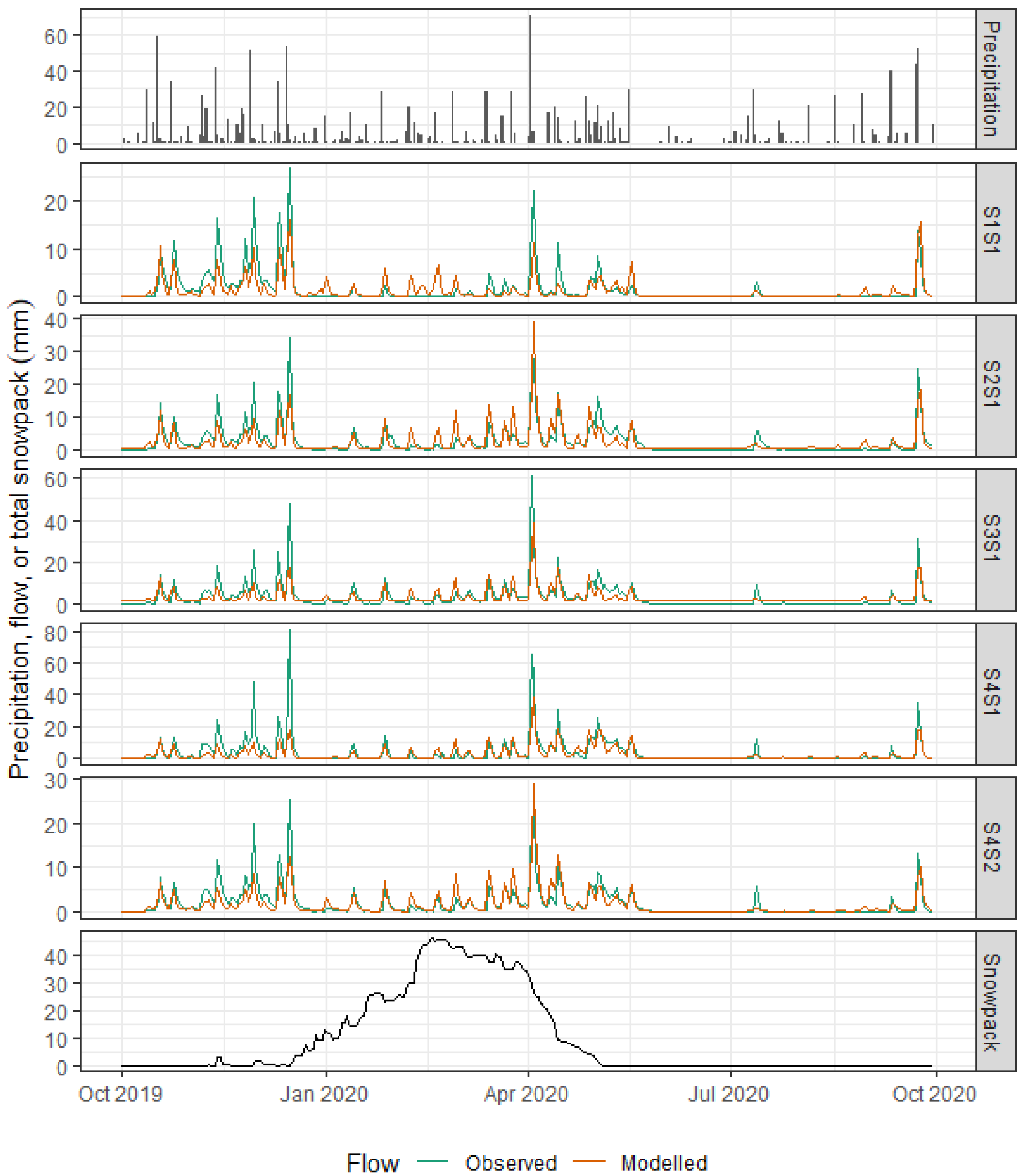
	Carbon from: (in order of operations)		
Receiving Pool:	**Wind Transfers**	**Decay (P_t)**	**Physical Transfer**
Stemsnag	*NIL*		
Branchsnag	*NIL*		
VFastAG	VFastAG (100%) Fine (50%) Foliage (100%)		
FastAG	Branchsnag (100%) FastAG (100%) Coarse (50%) Other (85%)		
Medium	Stemsnag (100%)* Medium (100%) Merch & Bark (15%)*		
SlowAG	SlowAG (100%)	Stemsnag (@0.17 x a_k) Branchsnag (@0.17 x a_k) Medium (@0.17 x a_k) FastAG (@0.17 x a_k) VFastAG (@0.185 x a_k)	
VFastBG	VFastBG (100%) Fine (50%)		
FastBG	FastBG (100%) Coarse (50%)		
SlowBG	SlowBG (100%)	VFastBG (@0.17 x a_k) FastBG (@0.17 x a_k)	SlowAG (@0.006)

* Remaining 85% of Merch goes to Product; all Stemsnag and Branchsnag lost to Medium and FastAG pools, respectively

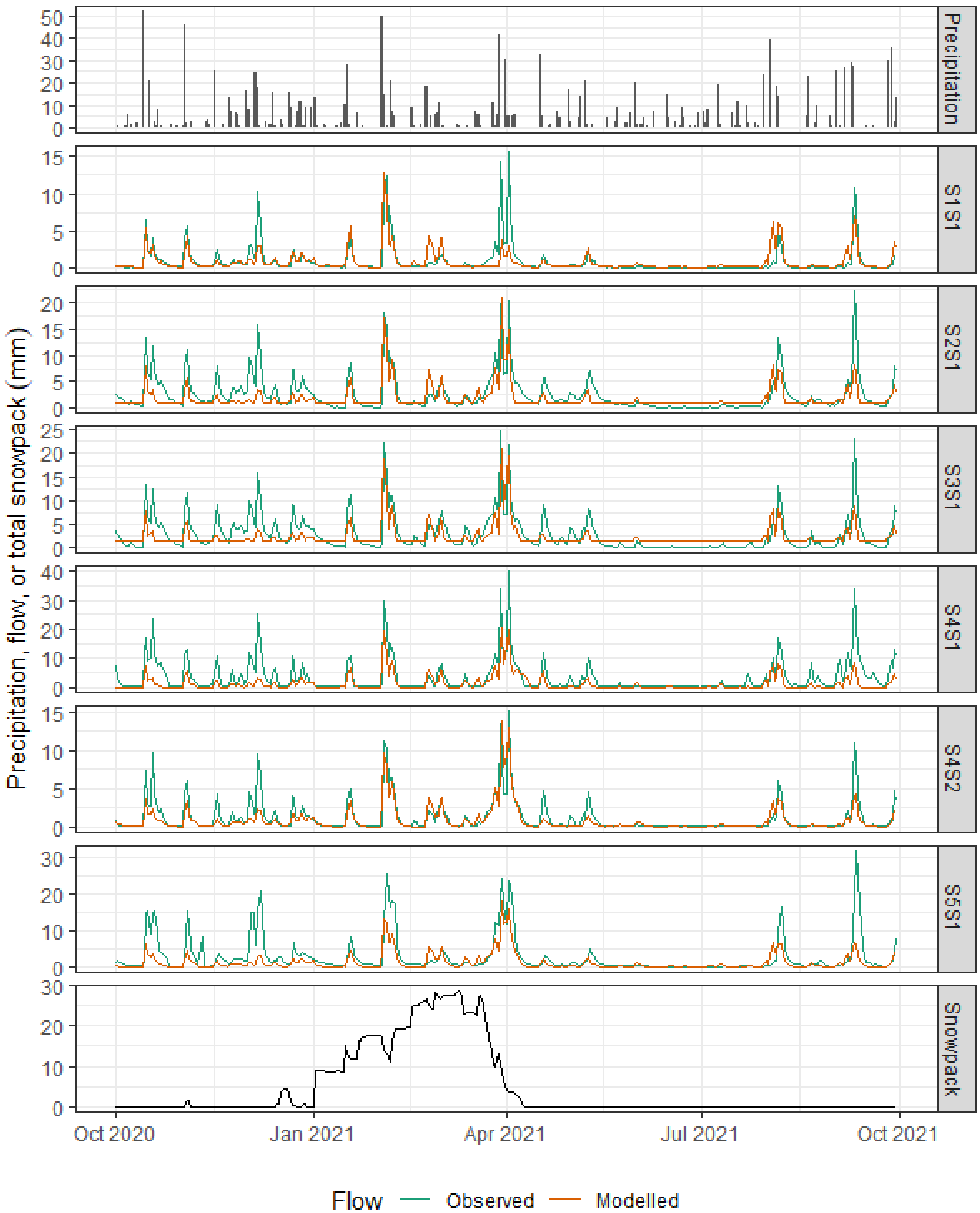
Appendix 2: Annual Hydrographs for Calibration Period

The following charts display precipitation records (mm day^{-1}), observed and modelled flow (mm day^{-1}), and average total snowpack (mm) for monitored subcatchments (S1S1 to S5S1) in the Pockwock watershed for varying periods. Observed flows were determined with continuous depth records and ratings curves generated by the researchers. Modelled flows are the results of calibration of HBV-light.

2019

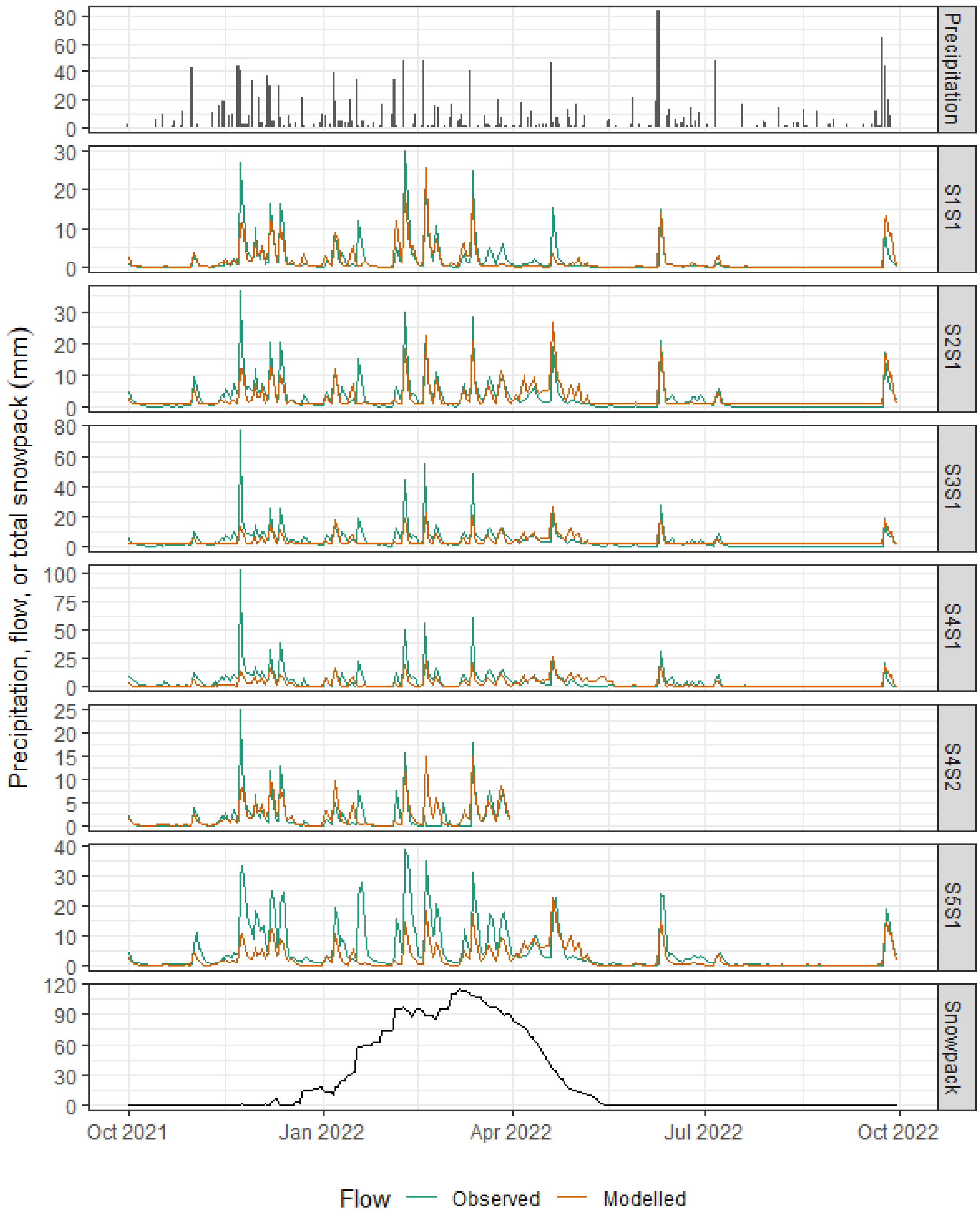


2020



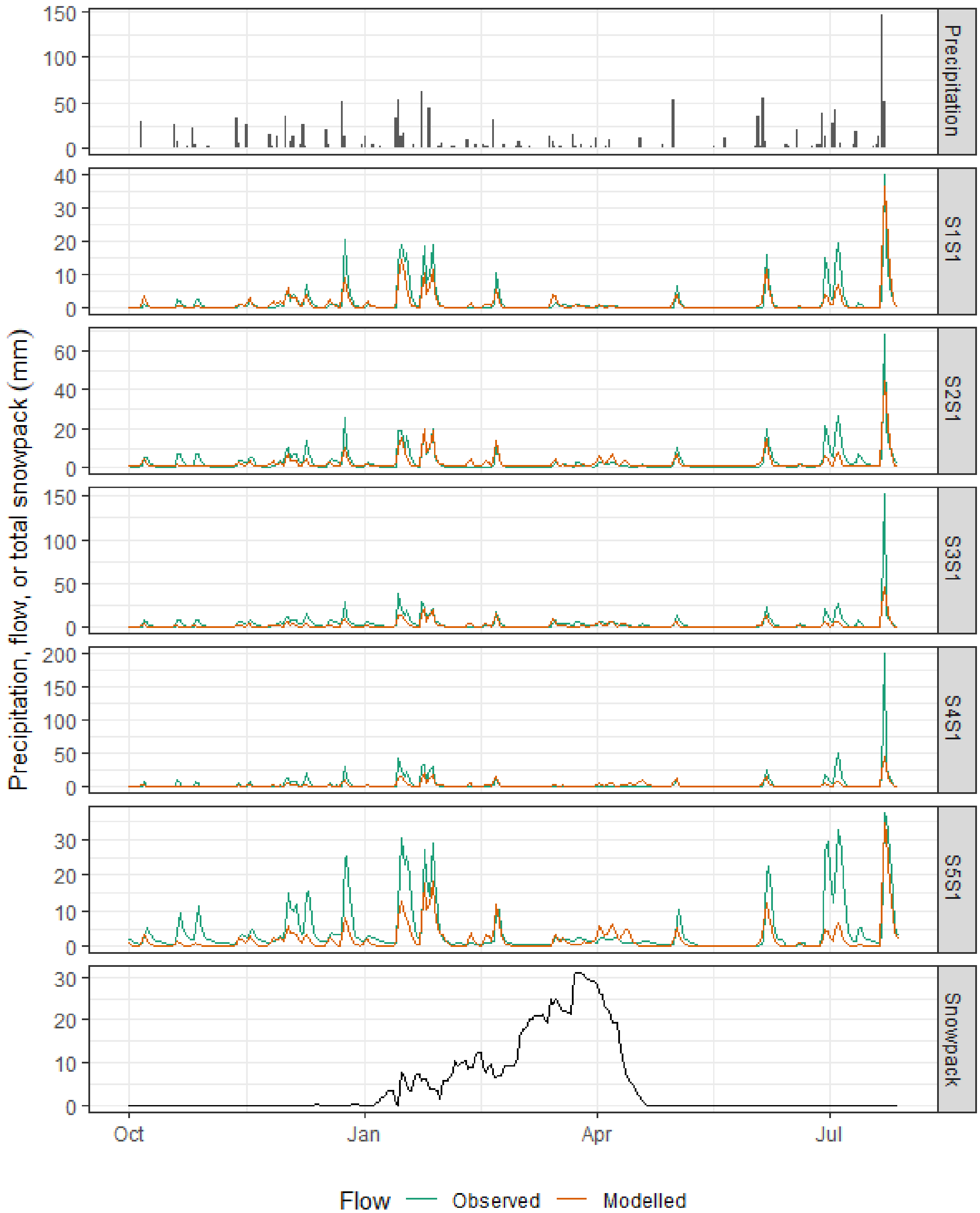
Precipitation, flow, or total snowpack (mm)
Precipitation
S1S1
S2S1
S3S1
S4S1
S4S2
S5S1
Snowpack
Oct 2020
Jan 2021
Apr 2021
Jul 2021
Oct 2021
Flow
Observed
Modelled

2021



Precipitation, flow, or total snowpack (mm)
Precipitation
S1S1
S2S1
S3S1
S4S1
S4S2
S5S1
Snowpack
Oct 2021
Jan 2022
Apr 2022
Jul 2022
Oct 2022
Flow
Observed
Modelled

2022


Precipitation, flow, or total snowpack (mm)
Precipitation
S1S1
S2S1
S3S1
S4S1
S5S1
Snowpack
Oct
Jan
Apr
Jul
Flow
Observed
Modelled