Literature review and jurisdictional scan of climate-change and carbon considerations in mine-reclamation planning

PREPARED FOR

Ministry of Energy, Mines, and Low Carbon Innovation (EMLI)

PREPARED BY

J. Straker & P. Porto

Integral Ecology Group

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Ministry of Mines, Energy, and Low Carbon Innovation
6th Floor, 1810 Blanshard Street, Victoria, BC V8T 4J1

ATTENTION: MARTINA BEZZOLA

REFERENCE: LITERATURE REVIEW AND JURISDICTIONAL SCAN OF CLIMATE-CHANGE AND CARBON CONSIDERATIONS IN MINE-RECLAMATION PLANNING

Dear Martina:

Please find following our draft report on the literature review and jurisdictional scan of climate-change and carbon considerations in mine-reclamation planning.

We trust this information meets your requirements at this time and thank you for the opportunity to contribute to this important project. Should you have any questions or comments, please do not hesitate to contact me at the email or phone number listed below.

Yours sincerely,

Justin Straker, M.Sc., P.Ag. (BC, AB, SK, ON)
Integral Ecology Group Ltd.
Soil Scientist, Reclamation Ecologist
jstraker@iegconsulting.com
250 701 0600

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EXECUTIVE SUMMARY

In this report, we present a literature review and jurisdictional scan on climate-change factors, ecosystem carbon accounting approaches, and carbon-sequestration techniques related to mine reclamation. Key findings, information gaps, and recommendations are discussed with the goal of assisting the British Columbia (BC) Ministry of Energy, Mines and Low Carbon Innovation (EMLI) with the development of policy, guidance, and tools for the integration of climate-change and carbon considerations into the management and reclamation of major mines in BC.

In summary, we identify a few tools that can facilitate the incorporation of climate-change factors into mine-reclamation planning and provide examples of how climate change is considered in other jurisdictions. We describe seven ecosystem carbon-accounting models developed primarily for forest ecosystems, and identify different carbon-assimilation techniques, ranging from wetland reclamation to the application of organic amendments to mine soils. Information gaps include the lack of validation or development of carbon-accounting models for mine-reclamation settings and carbon-rich ecosystems, and the lack of information on the benefits of using different carbon-sequestration approaches and their effect on biodiversity goals.

We recommend that EMLI consider instructing proponents to include explicit, specific, and quantitative considerations of climate change in their reclamation planning, using a climate-shifted baseline for assessing the achievement of equivalent capability.

A Tier 3 modelling approach is suggested to account for carbon in mine-reclamation ecosystems, because it can be used to evaluate different mine-reclamation scenarios and estimate pre- and post-mine conditions that do not yet or no longer exist, and also has the required resolution to provide results that are meaningful to management of mine development and reclamation.

Finally, we suggest that the primary strategies for promoting carbon retention and assimilation for mine development and reclamation should involve a hierarchical approach of (1) minimizing disturbance of carbon-rich ecosystems, (2) maximizing retention of soils and non-merchantable biomass, and (3) applying additional organic amendments to increase the carbon content of soils.

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GLOSSARY OF TERMS

BC	British Columbia
BEC	Biogeoclimatic Ecosystem Classification
C	Carbon
CaMP	Canadian Model for Peatlands
CASMOFOR	Carbon Sequestration Model for Forestations
CBM-CFS	Carbon Budget Model of the Canadian Forest Sector
CBM-CFS3	Carbon Budget Model of the Canadian Forest Sector (version 3)
CBST	Climate Based Seed Transfer
CCISS	Climate-Change Informed Species Selection
CFS	Canadian Forest Service
CH_4	Methane
cm	centimeter(s)
CO	Carbon monoxide
CO_2	Carbon dioxide
ECCC	Environment and Climate Change Canada
EFISCEN	European Forest Information Scenario
FORCARB	Forest Carbon Budget Model
FullCAM	Full Carbon Accounting Model
EMLI	Ministry of Energy, Mines, and Low Carbon Innovation
GCBM	Generic Carbon Budget Model
GHG	Greenhouse gas
ha	hectare(s)
IAA	Impact Assessment Act
IEG	Integral Ecology Group
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change, and Forestry
Mg	Megagram, equivalent to a metric ton
N_2O	Nitrous oxide
NIR	National Inventory Report
NPK	Nitrogen, phosphorus, and potassium
QEA	Quantitative Ecohydrological Analysis
RCP	Relative concentration pathway
SACC	Strategic Assessment of Climate Change
SOC	Soil organic carbon
SOM	Soil organic matter
US	United States
yr	year

1. INTRODUCTION

The central goal of this project was to conduct a literature review and jurisdictional scan to assist the BC EMLI in its planned integration of climate-change and carbon considerations into the management and reclamation of major mines in BC. More specifically, EMLI intends to develop carbon-accounting guidelines to support proponents in quantifying pre-disturbance carbon-storage capabilities, as well as identifying opportunities to integrate carbon sequestration within reclamation and closure planning and implementation.

2. OBJECTIVES AND APPROACH

The objectives of the literature review and jurisdictional scan were to address the following three topics, with a target of reviewing information from a minimum of four to five jurisdictions within BC, Canada, and internationally:

1. to what extent climate change factors are incorporated into mine reclamation planning, including relevant examples or scenarios of real-world applications where practicable;
2. current ecosystem carbon accounting systems used by governments, industry, or other entities that may be applicable for mine reclamation scenarios; and
3. carbon sequestration techniques and technologies utilized in mine site reclamation and ecosystem restoration, including relevant examples where practicable.

Additionally, the project report was to:

- provide key findings for each topic and high-level recommendations on which factors, systems, and techniques are recommended for further consideration for integration into future guidance and tool development within BC;
- provide recommendations on how to incorporate key findings into provincial policy, guidance, and tools for major mines in BC; and
- identify critical information gaps for the development of guidance for pre- and post-disturbance carbon accounting tools and including carbon storage in mine reclamation.

To meet the project objectives, we used a combination of standard literature-review techniques and interviews with subject-matter experts.

Literature was found by searching for key words (Table 1) in academic search engines (Google Scholar[1] and Summon by the University of BC[2]), conference repositories (BC Mine

[1] Google Scholar

[2] https://www.library.ubc.ca/

Reclamation Symposium[3] and Mine Closure[4]), and non-academic search engines (Google[5]); through personal communication with Integral Ecology Group (IEG) colleagues and external subject-matter experts; and through the reference list of related literature.

Interviews were conducted with Dr. Clive Welham and Dr. Werner Kurz. Dr. Welham is a forest ecologist and an expert in carbon management and accounting, and complemented our knowledge on local, national, and international approaches to carbon accounting and carbon sequestration. Dr. Kurz works for the Canadian Forest Service (CFS), where he leads the development of a National Forest Carbon Accounting System for Canada. He is an adjunct professor at the University of BC and Simon Fraser University, and a member and lead author of the Intergovernmental Panel on Climate Change (IPCC). His research focuses on the impacts of natural disturbances, forest management, and land-use change on forest carbon budgets.

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3 Repository for BC Mine Reclamation Symposium through UBC Library

4 https://papers.acg.uwa.edu.au/f/mineclosure

5 https://www.google.com/

Table 1. Non-exhaustive list of search terms used during the literature review.

Search engine	Topic	Search terms
Google Scholar	Climate change	Climate change mine reclamation
Summon	Climate change	Climate change mine reclamation
BC Mine Reclamation Symposium	Climate change	Climate change
Mine Closure	Climate change	Climate change
Google Scholar	Carbon accounting	Carbon modelling mine reclamation
Google Scholar	Carbon accounting	CBM CFS3 AND reclamation
Google Scholar	Carbon accounting	fullCAM forest Canada
Summon	Carbon accounting	fullCAM forest Canada
Google Scholar	Carbon accounting	fullCAM mine carbon
Google Scholar	Carbon accounting	fullCAM reclamation carbon
Google Scholar	Carbon sequestration	Carbon sequestration mine reclamation
Google Scholar	Carbon sequestration	Carbon sequestration ecosystem restoration
Google Scholar	Carbon sequestration	Comparison soil carbon storage mining
Google Scholar	Carbon sequestration	Green manure mine reclamation
BC Mine Reclamation Symposium	Carbon sequestration	Carbon sequestration
Mine Closure	Carbon sequestration	Carbon sequestration
Google	Carbon sequestration	Mine wetland restoration reclamation

3. SUMMARY OF RELEVANT LITERATURE AND APPROACHES

3.1. CLIMATE-CHANGE FACTORS

Ecological aspects of mine-reclamation planning have typically either discussed climate change in relatively generic ways, or implicitly assumed the stationarity of climate, but this latter assumption is no longer correct (Rooney et al., 2015).[6] In BC, ecosystems have already shifted due to climate change, and because of the lag between climate shifts and tree species distribution, species mixes that were historically successful, or even currently occupy similar areas, may not be successful in the coming decades (MacKenzie & Mahony, 2021).

With the intention of providing guidance to practitioners, Rooney et al. (2015) outlined a framework, using the reference-condition approach and bioclimate envelope models, to improve the success of large reclamation projects in a changing climate. The reference-

[6] Hydrological and geotechnical aspects of mine-reclamation planning are more advanced with respect to climate change, and typically explicitly incorporate projections of future climate conditions in calculating precipitation and runoff design events.

condition approach uses a comparable, undisturbed ecosystem as the baseline against which to evaluate the degree of disturbance to an ecosystem; and bioclimate envelope models use climate, hydrology, and species occurrence to map the distribution of viable species populations over time as the climate changes.

The authors recommended a six-step process for integrating climate-change considerations and the reference-condition approach for local and landscape-scale reclamation:

1. Climate model: use multiple models and scenarios to identify potential future climate conditions and uncertainties.
2. Hydrological model: estimate the impact of climate change on hydrology and establish a water budget for reclamation.
3. Bioclimate classification: combine climate and hydrologic variables with the bioclimate classification approach to identify self-sustaining reclamation targets.
4. Landscape model: identify reference landscapes from low-disturbance regions that are currently within the expected future climatic conditions and have similar geomorphology and soils to the mined area. Characterize their habitat composition and configuration at the landscape level.
5. Habitat model: define patch-level targets by characterizing the biotic and abiotic conditions of habitats or ecosites within reference landscapes.
6. Closure plan design: create climate-appropriate reclamation targets at the landscape-level by organizing self-sustaining habitat patches in the same configuration as the reference landscapes.

Currently, explicit and detailed consideration of climate change factors is relatively rare in mine reclamation planning in British Columbia, particularly as described in the published record. Searching the repository of papers from the BC Mine Reclamation Symposium yielded very few results related to climate-change, with the exception of papers on the Quantitative Ecohydrological Analysis (QEA) model developed by IEG and papers related to the carbon-sequestration (and climate-change-mitigation) benefits of applying biosolids to mine covers.

Below we introduce tools currently used or with the potential to be used in mine reclamation planning, and examples of climate-change considerations in reclamation.

3.1.1. British Columbia

ClimateNA

ClimateNA[7] is a Microsoft Windows and web-browser application developed by researchers from the University of BC, University of Alberta, Ministry of Forests, Lands and Natural Resources Operations of BC, and Klamath Center for Conservation Research (T. Wang et al., 2016). The application uses long-term weather-station records and global climate models to make downscaled climate estimates for any point in North America from 1901 to 2100. For future time periods, data is modelled for numerous climate-change intensities (i.e., relative concentration pathways [RCPs] or shared socioeconomic pathways). A version of the application exists just for BC and is called ClimateBC. The ClimateBC version incorporates modelling of shifting biogeoclimatic zones and variants in the province.

Climate-change informed species selection (CCISS) tool

The climate-change informed species selection (CCISS) web-based tool was developed by the Government of British Columbia to support decision-making by reforestation practitioners[8] (MacKenzie & Mahony, 2021). It uses the BEC system, provincial climate data from ClimateNA/BC, and an ensemble of global climate models to provide spatially explicit reforestation feasibility ratings by tree species and site series for different climate-change intensities and time periods ranging from 2021 to 2100. The tool can be used to assist in the selection of reforestation species, based on projections of how the climate will change at that location and which species will adapt well to that change. MacKenzie & Mahony (2021) also recommend using a diversity of tree species to maximize forest resilience and productivity, because there are always modelling uncertainties and factors not considered by bioclimate modelling.

Climate Based Seed Transfer (CBST) Seedlot Selection Tool

The Climate Based Seed Transfer (CBST) Seedlot Selection Tool is a web-based application[9] developed by the BC Ministry of Forests, Lands, Natural Resources Operations, and Rural Development. The CBST is the primary tool for determining appropriate seedlots for reforestation of Crown land in BC and is specified for current use in the *Chief Forester's Standards for Seed Use* (Nicholls, 2022). It allows users to find appropriate seedlots (for

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[7] https://climatena.ca/

[8] https://thebeczone.ca/shiny/ccissdev/

[9] https://maps.forsite.ca/204/SeedTransfer/

propagation of seedlings for use in reclamation programs) based on the location and climate of their reclamation site and current/expected climate changes.

Quantitative Ecohydrological Analysis (QEA) tool

The QEA tool was developed by IEG to support practitioners in mine reclamation planning (Baker et al., 2021). The key information provided by the tool can be divided into two groups: (1) predictions of site series and ecological-classification parameters within BC's Biogeoclimatic Ecosystem Classification (BEC) system, and (2) water-balance parameters. The tool uses soil characteristics, topography, and location-specific climate data obtained from ClimateNA/BC to make predictions for historical, current, and future time periods. The ecologically focused outputs allow users to explore expected ecological outcomes with a given set of soil and site characteristics, and plan for the return of pre-mine ecosystems through the design of landforms (e.g., slope gradient and aspect) and soils (e.g., texture and depth of cover soils and waste materials). The hydrological outputs are designed to inform long-term water-balance estimates at the landform and mine scales. The QEA tool has been used for mine-reclamation planning and comparisons of equivalent capability with explicit consideration of changing climate at the Gibraltar, Highland Valley Copper, Telkwa, and Quintette mines. Although primarily used internally by IEG, the QEA tool has a public-facing, web-based application.[10]

3.1.2. Canada

Nenzén et al. (2020) used a landscape model (LANDIS-II) to simulate the response of boreal forests to climate change and disturbances in the Alberta oil-sands region. LANDIS-II predicted that the most severe climate scenario (RCP8.5) would lead to large decreases in forest biomass and a shift in plant composition to drought- and fire-tolerant species, characteristic of parkland or prairie ecosystems; for RCPs 2.6 and 4.5, the model predicted that there would be relatively minor effects on forest composition and biomass. The authors concluded that under the RCP8.5 scenario, it would be difficult to meet the current reclamation goals of re-establishing spruce-dominated boreal forest ecosystems.

Alam et al. (2018) projected the hydrology of two reclamation sites at an oil-sands mine in Alberta using a water-balance model with baseline and future climate data for three RCPs. The model predicted an increase in net percolation for all RCPs and future time periods in the 21st century, which implies higher risks of contamination of downstream receptors and potential instability of waste dumps and containment structures from rising water tables.

[10] https://qea.iegsoil.com/reports/

Botula et al. (2019) discussed the impact of shifting species distributions due to climate change on the performance of engineered covers at a copper and nickel mine in Québec. Differences in leaf-area index, maximum root depth, and root density of current and future vegetation can impact the water balance of covers that are saturated with water to prevent oxidation and acid generation. The authors confirm that species composition is expected to change in that region, but have not yet modelled the combined influence of vegetation parameters and climate change (i.e., increasing precipitation) on the long-term performance of engineered covers/oxygen barriers.

3.1.3. Internationally

Rissik & Iles (2022) outlined a climate-change risk assessment of the mine-closure plan of a uranium mine in the Northern Territory of Australia. This climate-change risk assessment was conducted in agreement with recommendations from the International Council on Mining and the International Risk Management framework (ISO3100). The assessment included identifying climate-change scenarios, spatiotemporal boundaries, and key stakeholders to include in the assessment. Risks and vulnerabilities were assessed for each time frame, climate-change scenario, and planned closure activity. The magnitude and likelihood of climate risks were estimated, using a scoring system developed by Rio Tinto, for the following categories: onsite environment, offsite environment, compliance, and health and safety for staff. The analysis showed that risks were low for the 2030s projected climate but increased in quantity and severity in the 2050s and 2100s. Regarding revegetation, the impacts of heat, drought, and bushfire were considered in the selection and distribution of species across the reclamation landscape. Vegetation lost or damaged due to climate-related pressures would be replaced until the area meets closure criteria, after which any climate impacts would be considered unrelated to mining activities. The planting of fire- and drought-resistant species from drier areas south of the mine was considered, but decided against, because the rehabilitation goal for that region was to establish vegetation with characteristics similar to plants in the surrounding area, including in terms of resilience. Climate-change impacts to the transport of contaminants and erosion were also discussed in the paper.

3.2. CARBON ACCOUNTING SYSTEMS

3.2.1. Approach and focus

The Strategic Assessment of Climate Change (SACC) was developed by Environment and Climate Change Canada (ECCC) under section 95 of the Impact Assessment Act (IAA)[11]. It describes the climate-change information that designated project proponents need to submit as part of the federal impact assessment and requires projects extending beyond 2050 to submit a plan outlining how net-zero emissions will be achieved by 2050. The principles and objectives outlined in the SACC will also be used to build guidance for the review of non-designated projects on federal lands under IAA. The SACC is to be updated by Environment and Climate Change Canada every five years.

A technical guide was developed to describe in more detail how greenhouse gas (GHG) emissions and impacts to carbon sinks should be estimated for projects required to report this information. The SACC technical guide adapts the IPCC's tiered approach to a project/site level, using the definitions shown below. This is a useful adaptation for EMLI's purposes, as it is directly applicable to the goal of understanding and managing carbon stocks and fluxes for mine development and reclamation.

- **Tier 1** is a generic approach and uses a clearly defined framework for calculations as well as default international parameters provided in the IPCC guidelines (Eggleston et al., 2006), or national parameters drawn from the National Inventory Report (NIR), but not specifically applicable to the precise location.
- **Tier 2** uses the same methodological framework for calculations as in Tier 1 above but replaces the IPCC Tier 1 default values or derives default factors using standardized functions with site- or regionally specific data.
- **Tier 3** is a site-specific approach and involves tracking the relevant carbon stocks, as well as the transfers between them and to the atmosphere, through time. This can be done through comprehensive field surveys repeated regularly over time, or through a country-specific Tier 3 model, using data from the site as model input.

The SACC technical guide uses a decision tree (Figure 1) to provide direction on which tiered approach to use to for carbon accounting. We believe that this decision tree may be useful as a basis—albeit potentially with modifications—for guiding carbon-accounting guidelines for major mining projects in BC.

[11] https://www.strategicassessmentclimatechange.ca/

For this review, we focused on reviewing available Tier 3 carbon accounting models, since both Tier 1 and Tier 2 approaches can use equations already developed by IPCC, and may have insufficient precision and accuracy to usefully assess changes to ecosystem carbon at the scale of an individual mining project. In addition, because there is a large body of literature that addresses ecosystem carbon accounting, we focussed on work that has the highest potential to be applied to mine development and reclamation.

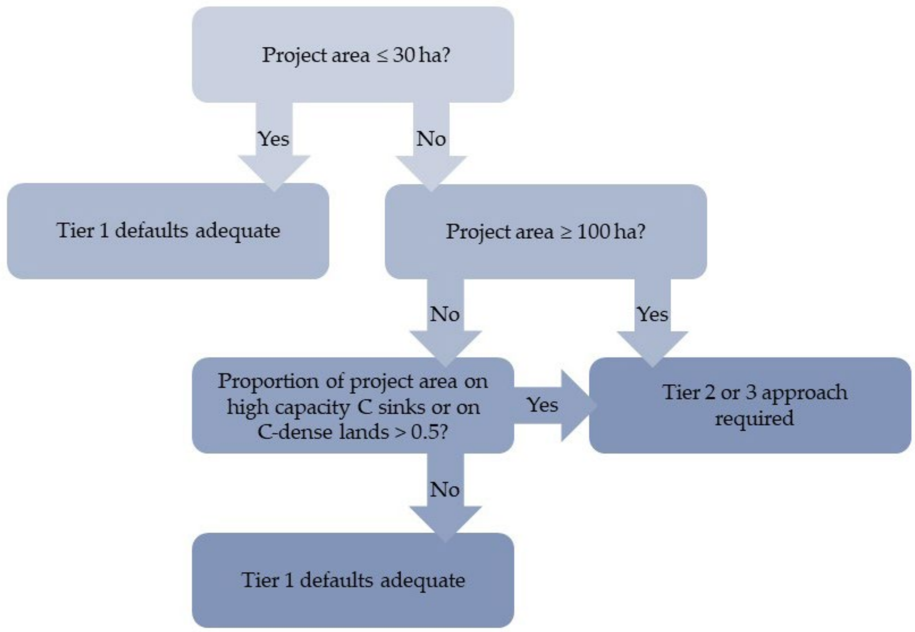

Figure 1. Decision tree, modified from Environment and Climate Change Canada (2021), used to determine which tiered approach is required for estimating greenhouse-gas emissions or impacts to carbon (C) sinks. Areas with high C-sink capacity include young- to medium-aged forests, forested wetlands, and bogs. Carbon-dense areas include mature forests, forested wetlands, and wetlands.

3.2.2. British Columbia and Canada

Operational-Scale Carbon Budget Model of the Canadian Forest Sector

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) was developed beginning in the late 1980s to meet the operational-scale forest carbon accounting needs of forest managers and analysts across Canada.[12] The CBM-CFS3 (version 3 of the model) is a stand- and landscape-level modeling framework that can be used to simulate the dynamics of

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[12] A self-guided 12-hour online course is available for practitioners willing to learn how to use the model (https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107#download).

all forest carbon stocks required under the United Nations Framework Convention on Climate Change, to which Canada submits its National Inventory Report (NIR) annually (Ministry of Environment and Climate Change Strategy, 2022). CBM-CFS3 is compliant with the carbon estimation methods outlined by the IPCC.

The CBM-CFS3 is an empirical, aspatial (forest stands are not spatially referenced) model that runs at a yearly timestep and simulates carbon dynamics at a stand and landscape-level (Kull et al., 2019; W. Wang et al., 2016). It uses forest inventory data (species composition, stand age, etc.), empirical growth and yield curves, and information on natural and anthropogenic disturbances to estimate changes to the following carbon pools: above- and below-ground biomass, litter, deadwood, and soil organic carbon (Kull et al., 2019). Examples of natural and anthropogenic disturbances available in the model include wildfire, insect damage, clear-cutting, salvage logging, commercial thinning, and controlled burning (Environment and Climate Change Canada, 2021b; Kull et al., 2019).

The CBM-CFS3 is currently used for ecosystem carbon accounting in BC—BC's yearly GHG Emissions Inventory Report provides provincial-level data for the land use, land-use change, and forestry (LULUCF) category, following the data and methodology from Canada's NIR (Ministry of Environment and Climate Change Strategy, 2022). For both reports the CBM-CFS3 is used to estimate changes in carbon stocks, emissions, and removals by managed forests, forest conversion to other land uses, and land converted to forest land (e.g., afforestation, reclamation) (Environment and Climate Change Canada, 2021b; Ministry of Environment and Climate Change Strategy, 2022).

The CBM-CFS3 is well-validated for Canadian forest ecosystems (Kurz et al., 2009) and has been used in a reclamation setting to successfully simulate carbon dynamics of 35 to 40-year-old pine plantations growing on copper-nickel mine tailings in Sudbury, Ontario (Metsaranta et al., 2018).

- **Limitations**
  - The effect of climate change on forest growth is not incorporated in the CBM-CFS3 model but can be simulated by adjusting input growth curves (see Ménard et al. 2022 for an example).[13] Furthermore, in the model, decomposition is only impacted by changes in temperature, and not by changes in precipitation (Kull et al., 2019).
  - The model is parameterized for forest ecosystems, and not for non-forest ecosystems such as wetlands and grasslands. The CBM-CFS3 architecture allows for tracking of

[13] The Carbon Accounting Team of the Canadian Forest Service are currently working on implementing climate-sensitive growth curves to the model, which may take 4-5 years until completion (K. Werner and J. Metsaranta, personal communication, February 13, 2023).

two ecosystem components for each area, so this architecture could be modified to incorporate grassland and wetland ecosystems, but these ecosystems would require parameterization.

- The model is not parameterized for reclaimed ecosystems, particularly for the starting carbon conditions of reclamation cover systems and retention of woody materials. However, this limitation is true of all reviewed approaches, and the CBM-CFS3's structure lends itself to relatively easy modification to address these factors.

The Generic Carbon Budget Model

The Generic Carbon Budget Model (GCBM)[14] is a version of the CBM-CFS3 linked to an open source, modular, spatially explicit modelling framework (Full Lands Integration tool) that was developed by experts from the Canadian Forest Service, Australia (Mullion Group), and the moja global organization (Shaw et al., 2021). This framework allows GCBM users to determine the scale of modelling, from fine to coarse (landscape), and requires users to provide input information in spatially explicit layers (Shaw et al., 2021). The GCBM is planned to eventually replace the CBM-CFS3 in Canada's National Forest Carbon Monitoring, Accounting, and Reporting System, but currently does not include a graphical user interface, requiring users to be familiar with Python programming language and Windows command line (Government of Canada, 2022).

Shaw et al. (2021) used the GCBM to model carbon dynamics in 1.3 million ha of upland forest in the oil-sands region of Alberta, which experienced both anthropogenic (forestry, energy sector) and natural (wildfire, insect) disturbances. With the help of subject-matter experts, the researchers developed new disturbance options within GCBM to better describe oil and gas exploration. Results showed that over 28 years, 25% of the study area was disturbed, causing it to change from a net carbon sink to a net carbon source. The largest cumulative disturbance emissions were caused by the energy sector, followed by wildfire, and then harvesting. This study did not include the contributions of wetlands (peatlands) to the estimated net GHG emissions, despite wetlands occupying almost half of the entire oil-sands region. Dr. Kelly Bona is working on updating the study by Shaw et al. (2021) to include wetland modelling (K. Bona, personal communication, February 13, 2023).

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[14] There is a self-guided training package for the GCBM freely available for download from the Canadian government website (https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/forest-carbon-accounting-tools/generic-carbon-budget-model/24366).

In another study, Bona et al. (2020) developed and tested a model for estimating carbon dynamics in peatlands, the Canadian Model for Peatlands (CaMP), which can be used as a module within GCBM. The current version of the CaMP (version 2.0) can simulate 11 different peatland categories and includes only wildfire as a disturbance, but provides the framework for including additional disturbances. CaMP can model the impact of hydrology on methane fluxes using the national Canadian Fire Weather Index Drought Code to predict large-scale, long-term, annual water table depth.

- **Limitations**
    - Limitations of the GCBM are similar to those of the CBM-CFS3, except that the CaMP module of the GCBM allows for the incorporation of wetland dynamics into ecosystem carbon accounting.

3.2.3. Internationally

Forest Carbon Budget Model

The Forest Carbon Budget (FORCARB) model was developed by the United States (US) Forest Service, which is part of the US Department of Agriculture. FORCARB is an empirical, aspatial, landscape-level model that simulates carbon stocks at 5-year timesteps (Heath et al., 2010). It can simulate both natural and anthropogenic disturbances, such as wildfire and forest harvesting, and estimates the following carbon pools: above- and below-ground biomass, litter, deadwood, and soil organic carbon (Heath et al., 2010).

A version of this model, called FORCARB-ON (latest version: v2), was developed for forests in Ontario and contains more detailed fire disturbance and wood product modules (Ter-Mikaelian et al., 2022). It has been used to model forests in Ontario by Chen et al. (2010).

- **Limitations**
    - The model is parameterized for forest ecosystems, and not for other ecosystems such as wetlands and grasslands.
    - The effect of climate change on forest growth is not incorporated into FORCARB or FORCARB-ON.
    - We found no literature on the use of FORCARB or FORCARB-ON in mine reclamation sites.

Full Carbon Accounting Model

The Australian government uses the Full Carbon Accounting Model (FullCAM) to estimate GHG emissions and carbon stock changes within the LULUCF sector (Australian Government, 2022). FullCAM is an empirical and mechanistic model, with a 1-month timestep, that can be configured to run spatially or aspatially (Australian Government, 2022; W. Wang et al., 2016). FullCAM is compliant with IPCC guidelines. It estimates GHG emissions (CO_2, CH_4, N_2O) and changes to carbon pools, including above- and below-ground biomass, litter, deadwood, and soil organic matter.

FullCAM can be used to simulate forests, cropland, grasslands, and any land-use transitions between these categories (Australian Government, 2022). The model is also used to estimate emissions and removals from the conversion of forest to flooded lands (i.e. dams), and mangrove wetlands to settlements, grassland, or cropland (Australian Government, 2022). FullCAM consists of submodels which can be used independently or in combination for simulating forests (CAMFor module), cropping and grazing systems (CAMAg module), soil carbon (Rothamsted Soil Carbon model), and wetlands-coastal ecosystems (Australian Government, 2022). FullCAM can also simulate natural and anthropogenic ecosystem disturbances, such as wildfire, land clearing, harvesting, and forest planting (Australian Government, 2022).

- **Limitations**
  - FullCAM may have a useful structure for ecosystem carbon accounting for major mine-reclamation projects, but we found no literature on the use of FullCAM to simulate Canadian ecosystems or reclaimed mine sites.
  - The effect of climate change on forest growth and disturbances is not incorporated into FullCAM, but external models can be used to provide climate-impacted inputs to FullCAM. Pinkard et al. (2014) estimated future carbon stocks of a eucalyptus plantation with FullCAM by first using an insect-damage model and a biomass-productivity model to estimate annual biomass inputs in future climate scenarios.

Carbon Sequestration Model for Forestations

The Carbon Sequestration Model for Forestations (CASMOFOR) was developed by the Hungarian Forest Research Institute to estimate the carbon balance of managed forests and afforestation scenarios at both the stand- and landscape-level (Somogyi, 2019). It was designed for use in Hungary but could be applied to other countries if data is available (Kim et al., 2015; Somogyi, 2019). CASMOFOR is aspatial, and uses management information, growth and yield curves, and other parameters to estimate carbon stock changes at a yearly timestep. The model is based on IPCC methodologies and the estimated carbon pools include above- and below-ground biomass, litter, deadwood, and soil organic matter. Modelled disturbances include tree thinning and cutting (Somogyi, 2019). CASMOFOR can also calculate the costs and revenues from all forestry operations. The model is user-friendly, transparent, and runs on Microsoft (MS) Excel and MS Visual Basic (Somogyi, 2019).

- **Limitations**
    - CASMOFOR does not model natural disturbances.
    - Similarly to other reviewed model, the effect of climate change on forest growth is not incorporated into CASMOFOR, but climate-impacted inputs can be used with the model to estimate climate-impacted carbon stocks. See Somogyi (2016) for an example.
    - We found no literature on its application with Canadian ecosystems or mine reclamation sites.

CO2FIX

CO2FIX was financed by the European Commission (INCO2-progreamme) and is an empirical, aspatial, stand-level model that simulates carbon stocks and GHG fluxes (CO_2, CH_4, N_2O) in forests at yearly timesteps (Schelhaas et al., 2004; W. Wang et al., 2016). It can model the following carbon pools: above- and below-ground biomass, litter, deadwood, and soil organic matter; and simulates both natural and anthropogenic disturbances, such as wildfire, forest harvesting, insect and wind damage. The user manual has instructions for simulating 'special cases' like grasslands and coppice systems, but the model was not built for this application. CO2FIX simulates the carbon cycle in forest soils using the YASSO module, and also contains a bioenergy and a financial module, which can be used to calculate reduced emissions from bioenergy production. Gaboury et al. (2009) used CO2FIX to simulate carbon stocks in afforested boreal ecosystems in Quebec.

- Limitations
    - We found no literature on the use of CO2FIX to model carbon stocks in mine reclamation sites.
    - The effect of climate change on forest growth is not incorporated into CO2FIX but can be simulated using process-based models to create climate-impacted inputs for CO2FIX. However, underlying processes, such as allocation and turnover patterns, are not impacted when using this method.

European Forest Information Scenario Model

Development of the European Forest Information Scenario (EFISCEN) model started in the 1980s by Professor Ola Sallnäs at the Swedish Agricultural University (Verkerk et al., 2017). Since then, many researchers and organizations (mainly the European Forest Institute and Alterra) further developed the model into its latest version, EFISCEN 4. EFISCEN is designed to simulate even-aged, managed forests at a landscape level (regional or national) and at 5-year timesteps; it can be applied to smaller areas, but this application has not been well-studied, and uncertainties are unknown. EFISCEN has the option for spatially referencing regions for mapping, and uses a range of inputs, including growth and yield data, to estimate changes to carbon stocks, such as above- and below-ground biomass, litter, deadwood, and soil organic matter. Data on litterfall, felling residues, and natural tree mortality are used by YASSO to estimate forest soil carbon stocks, which is the same soil sub-model used in CO2FIX (Schelhaas et al., 2004; Verkerk et al., 2017). EFISCEN can simulate the impact of forest management and climate change on forest growth, and can model thinning, felling, and afforestation.

- Limitations
  - EFISCEN does not model natural disturbances and we found no literature on its use to model carbon stocks in mine reclamation sites or Canadian ecosystems.
  - The application of EFISCEN for modelling smaller areas has not been well-studied and has unknown uncertainties.
  - EFISCEN is not well-suited for modelling large-scale deforestation disturbances.

Spreadsheet accounting approaches

In addition to CASMOFOR, some ecosystem carbon accounting approaches involve the use of spreadsheet models. Many of these spreadsheet models require modelling subroutines, e.g., use of a forestry model to provide estimates of above-ground biomass over time, which are in turn tracked in the spreadsheet model. These spreadsheet models appear to be generally proprietary, i.e., run by individual firms engaged in carbon accounting—we did not find published references to spreadsheet-based ecosystem carbon accounting for mine-reclamation projects.

Table 2. Summary of forest carbon accounting models.

Model Acronym	CBM-CFS	GCBM	FORCARB	FullCAM	CASMOFOR	CO2FIX	EFISCEN
Organization	Canadian Forest Sector		US Department of Agriculture's Forest Service	Australian Government	Hungarian Forest Research Institute	European Commission (INCO2-programme)	European Forest Institute
Time step	1 year		5 years	1 month	1 year	1 year	5 years
Scale	Stand- and landscape- level		Landscape-level	Stand- and landscape-level	Stand- and landscape-level	Stand-level	Landscape-level
Spatial or aspatial?	Aspatial	Spatial	Aspatial	Both	Aspatial	Aspatial	Both
Carbon stocks modelled	Includes above- and below-ground biomass, litter, deadwood, and soil organic matter.						
Disturbance types available	Natural and anthropogenic such as wildfire, insect damage, harvesting, and mining. Has the option to create new disturbances.		Wildfire and forest harvesting.	Land use changes, and includes wildfire, land clearing, harvesting, and forest planting.	Afforestation, tree thinning and cutting.	Includes wildfire, insect and wind damage, and forest harvesting.	Afforestation, deforestation, tree thinning, felling, climate change.
Modelled ecosystems	Forests	Forests and peatlands (CaMP module).	Forests	Forests, croplands, grasslands.	Forests	Forests and 'special cases' like grasslands and coppice systems, but was not built for the latter.	Forests

Model Acronym	CBM-CFS	GCBM	FORCARB	FullCAM	CASMOFOR	CO2FIX	EFISCEN
GHGs modelled	CO, CO_2, CH_4, and N_2O.		CO_2 emissions only.	CO_2, CH_4, and N_2O.	CO_2 emissions only.	CO_2, CH_4, N_2O.	CO_2 emissions only.
Has it been used to model Canadian ecosystems?	CBM-CFS3 is used for estimating carbon stocks for the LULUC sector in the Canadian NIR and is well-validated for Canadian ecosystems.		FORCARB-ON was used to model forests in Ontario – see Chen et al. (2010).	No papers found.	No papers found.	Yes, to model afforestation in Quebec – see Gaboury et al. (2009).	No papers found.
Has it been used to model mine reclamation sites?	Yes, Metsaranta et al. (2018) modelled pine plantations growing on mine tailings in Ontario.	Yes, Shaw et al. (2021) used GCBM to model natural and energy sector disturbances on forests in the oil-sands region of Alberta.	No papers found.	No papers found.	No papers found.	No papers found.	No papers found.

3.3. CARBON ASSIMILATION TECHNIQUES AND TECHNOLOGIES

3.3.1. Background

Carbon assimilation is the process of fixing atmospheric CO_2 into plant biomass through photosynthesis, and the attendant storage of carbon in long-lived plant tissues and soil organic matter (SOM) (Shrestha & Lal, 2006).[15] Carbon assimilation in reclaimed ecosystems is impacted by different factors, including reclamation methods, age of reclamation, vegetation characteristics, soil properties, and climate (Misebo et al., 2022).

Standard reclamation practices which address characteristics unfavourable to plant growth (i.e. extreme pH values, high soil bulk density, contaminants, etc.) help to increase carbon assimilation by improving plant productivity and subsequent organic matter inputs to the soil. Direct measurements of net ecosystem carbon exchange on reclamation sites in western Canada has indicated growing-season assimilation rates of 0.4-1.6 Mg ha^{-1} yr^{-1} in relatively unproductive sites in central Yukon (Anderson et al., 2022) to higher rates of 1-5 Mg ha^{-1} yr^{-1} in productive upland mixed wood sites in Alberta's oil-sands region (Straker et al., 2019). Working on reclamation sites in Ohio, Akala & Lal (2001) observed that the rate of soil organic carbon (SOC) assimilation changed from 2-3 Mg ha^{-1} yr^{-1} in the initial reclamation period to 0.4-0.7 Mg ha^{-1} yr^{-1} after 20 to 30 years of pasture or forest land.

Several processes stabilize SOM and protect it from decomposition in the soil, such as aggregate formation and the formation of organo-mineral complexes. Soil aggregate formation and stability can be enhanced by organic matter additions and bioturbation (Misebo et al., 2022; Shrestha & Lal, 2006). In addition, proper storage and management of soil and woody materials can reduce carbon losses due to oxidation and erosion/leaching.

Some examples of carbon assimilation in mine-reclamation projects are listed by jurisdiction below:

3.3.2. British Columbia

Soil reclamation

Biosolids

Antonelli et al. (2018) compared the impact of a one-time municipal biosolids application on the carbon assimilation of pasture-based ecosystems at a copper and molybdenum mine (Highland Valley Copper) in British Columbia. They compared three treatments: a one-time application of biosolids at 150 and 250 dry Mg ha^{-1}, and a control (no biosolid application).

[15] Carbon assimilation can be a kind of carbon sequestration. We use the term assimilation in this report to distinguish from artificial carbon-sequestration approaches such as CO_2 capture and storage.

After 13 years, it was observed that above-ground plant biomass was substantially higher in the biosolid treatments, 6 and 6.7 Mg ha^{-1} in the 150 and 250 Mg ha^{-1} biosolid plots, compared to 0.39 Mg ha^{-1} in the unamended tailings. Total soil carbon was 172 and 106 g kg^{-1} in the 150 and 250 Mg ha^{-1} biosolid plots versus 13.7 g kg^{-1} in the control plots.

Trlica & Teshima (2011) compared the carbon stocks in biosolids-amended versus conventionally reclaimed (topsoil applications and/or NPK-fertilized) soils at five closed mines located in British Columbia (copper-molybdenum, sand and gravel), Washington (coal), Pennsylvania (coal), and New England (Massachusetts and New Hampshire, sand and gravel). The authors found that sites amended with biosolids stored significantly more soil carbon (33 ± 3 Mg C ha^{-1}, on average) than conventionally reclaimed sites at the 0-15 cm depth, but found no differences in soil carbon content at the 15-30 cm depth.

Abiotic carbon exchange

Wilson et al. (2009) described the natural process of carbon sequestration through the mineralization of carbonate minerals in chrysotile tailings from Clinton Creek, Yukon Territory, and Cassiar, BC. The authors mention that converting 10% of tailings by weight to carbonate minerals could offset GHG emissions from many ultramafic-hosted mines, and that other deposit types also have this capability. Savage et al. (2019) presented a case study for a Finnish nickel mine and assessed the potential for carbon sequestration and the mitigation of acid mine drainage with the alkaline by-products of the carbonation process. In contrast, dissolution of carbonates in tailings as a result of acid reactions can result in the evolution of carbon from mine tailings: Anderson et al. (2022) measured a release of 0.8-1.0 Mg C ha^{-1} yr^{-1} from a large tailings deposit in the Yukon.

3.3.3. Canada

Soil reclamation

Peat and biochar

Petelina et al. (2014) compared the impact of peat and biochar, both amended with synthetic fertilizer (NPK and sulphur), on total vegetation cover of a perennial seed mix (composed of grasses, forbs, and a shrub) grown on sandy borrow material at a uranium mine in northern Saskatchewan. After one growing season, the peat plus fertilizer treatment had approximately 2-5 times higher vegetation cover compared to biochar plus fertilizer, likely due to peat's higher water-holding capacity. Interestingly, higher rates of biochar led to a decrease in vegetation establishment. This study did not directly assess treatment effects on carbon assimilation.

Biosolids

Teshima & Lavery (2022) introduced a project that integrates biosolids application with the establishment of large-scale willow (*Salix spp*.) plantations at a mine-reclamation site at a coal mine in Alberta. Willow biomass grows fast and can be harvested every 3-4 years. Once harvested, it regrows from the base of the shrub. The authors asserted that the combination of biosolid applications and the decomposition of willow biomass (litter and roots) can enhance carbon sequestration, accelerate pedogenesis, and improve soil quality. As with the above study, this paper does not directly assess effects on carbon assimilation.

Wetland reclamation

Clark et al. (2019) measured CO_2 fluxes at a constructed-wetland reclamation project on an oil-sands mine in northeastern Alberta. The constructed wetland is characterized by three areas, a lowland region with saturated salvaged peat soils and wetland species, and midland and upland regions with moist salvaged peat soils and a mix of herbaceous, shrub, and tree species. Three years following the establishment of the wetland, the lowland region is in the early stages of carbon accumulation and was a net CO_2 sink, assimilating 0.8 Mg C ha^{-1} yr^{-1}, which is comparable to other undisturbed and restored wetlands. The midland and upland regions, due to both ecosystem and soil respiration (resulting from peat decomposition) were net carbon sources for the first three years following revegetation.

3.3.4. Internationally

Soil reclamation

Green manure

Green manure is a crop grown to be harvested and incorporated into the soil to enhance soil fertility by providing organic matter and nitrogen (especially if the green manure is a legume). It is typically associated with agricultural practices but can also be used to improve the quality of reclamation soils before revegetation. Pietrzykowski et al. (2017) explored the use of yellow lupine as a green manure prior to reforestation of opencast sand mining reclamation sites in Poland. Their study was a chronosequence of four treatments occurring over 4 years: 1 year of lupine cultivation (year 1), 2 years of lupine cultivation (year 2), 2 years of lupine cultivation plus 1 year of fallow (year 3), and 2 years of lupine cultivation plus 2 years of fallow (year 4). Plots were amended with local forest soils at the beginning of the study. Researchers found higher carbon stocks (lupine biomass + soil) in the treatments without fallowing. Nitrogen pools in the first year of growing lupine were not significantly different than the following 3 years, so given the reclamation effort, the authors recommended 1 year of lupine green manure before reforestation.

Soil amendments and cultural practices

Shrestha et al. (2009) carried out a field experiment at coal mine sites in eastern Ohio, to assess the impact of different reclamation practices on carbon stocks. The treatments involved adding cow manure (10 Mg ha^{-1}) and lime, oat straw mulch (15 Mg ha^{-1}) and NPK fertilizer, or chiseling (ripping to a 30-cm depth) in addition to the normal reclamation practice (control), which involved grading of the overburden, adding 30 cm of topsoil, seeding a grass-legume mix, and applying oat straw mulch (7 Mg ha^{-1}). After 5 years, mulching had no effect on carbon stocks (soil and biomass), but manure and chiseled plots had carbon stocks 25 to 27 Mg C ha^{-1} higher than the control.

Biochar

Ghosh & Maiti (2021) investigated the effect of applying biochar (made from invasive species *Calotropis procera*) at two rates, 30 Mg ha^{-1} (BC_{30}) and 60 Mg ha^{-1} (BC_{60}), to an 8-year-old afforested mine spoil in an open cast coal mine in the district of Jharkhand, India. After 6 months, there were no difference in biomass carbon, but total soil carbon at BC_{30} (36.3 g C kg^{-1}) and BC_{60} (40g C kg^{-1}) was significantly higher than the control (21 g C kg^{-1}), and similar to a nearby reference forest site (33 g C kg^{-1}).

4. INFORMATION GAPS

4.1. CARBON ACCOUNTING SYSTEMS

We identified the following primary information gaps related to ecosystem carbon accounting for mine reclamation:

- No models or other processes have been developed in a robust way for application to mine-reclamation settings. This makes sense, given that the impetus for developing these approaches has been the need for national carbon accounting, and mine development and reclamation have minimal effect on ecosystem carbon accounting at this scale. However, this means that none of the models/processes are usable for mine-project ecosystem carbon accounting in an “off-the-shelf” way, and all require modification for this purpose.
- The models with the most potential utility for mine-reclamation ecosystem carbon accounting are parameterized and tested for forest ecosystems, which make up the bulk of the land area affected by most mining projects in BC. However, they are not developed for use in non-forested and potentially carbon-rich ecosystems such as grasslands and wetlands, which are of interest to EMLI in this project. This gap may be partly filled through the development of the CaMP module addressing wetlands for the GCBM (the spatial version of the CBM-CFS3).

- We provide additional detail on information gaps in the Discussion section of this report.

4.2. CARBON SEQUESTRATION TECHNIQUES

Reclamation techniques to maximize carbon assimilation by reclaimed ecosystems are focussed on the use of organic-matter additions (e.g., biosolids/manure, mulch/green manure, biochar) to add SOM and increase carbon assimilation in biomass by increasing vegetation productivity. Two key information gaps in these approaches are:

- Quantification of the carbon-sequestration benefits of these organic-matter-addition approaches over reclamation approaches where these products are not used, or where less nutrient-dense amendments are used (e.g., wood chips, coarse woody debris).Whether these approaches can be used in concert with establishment of a broad suite of native plant species to achieve ecosystem and biodiversity goals, or whether they are most effective—at least for carbon assimilation—when used with dense and relatively non-diverse plantings of productive species such as willows and poplars.

5. DISCUSSION AND RECOMMENDATIONS

The following subsections provide discussion and our recommendations based on the results of this literature review and jurisdictional scan.

5.1. DO WE NEED A MODEL FOR ECOSYSTEM CARBON ACCOUNTING FOR MINE RECLAMATION?

There are alternatives to modelling approaches to ecosystem carbon accounting for mine reclamation. One is the use of simple, “look-up” tables for different ecosystem types, and the other involves empirical measurement of ecosystem carbon as an assessment tool. We believe that EMLI’s goal of understanding and managing carbon stocks and fluxes in mine reclamation likely requires a modelling (Tier 3) approach, for the following reasons:

- Evaluation of ecosystem carbon as a component of equivalent capability requires estimates of carbon stocks/fluxes for both a pre-mining baseline and post-reclamation conditions. In most cases, one of these conditions will require simulation, as it will either no longer exist (i.e., the baseline for an existing mine), or does not exist yet (e.g., reclamation for a proposed mine).
- Look-up-table (Tier 1 and 2) approaches likely do not have the resolution required to provide results that are meaningful to management of mine development and reclamation. For instance, the SACC technical guidance document provides default values for age and live biomass by ecozone, species, and productivity category for BC

(Table 3). These values could be used to estimate live biomass for baseline and reclamation conditions in the province, and could be appropriate for small mining projects, but would not support a very detailed evaluation of carbon changes resulting from mining and subsequent reclamation. In addition, they are incomplete, and provide information on only a portion of ecosystem carbon stocks. The SACC technical guide tells proponents that where default values are inadequate to meet objectives and additional information is required, they have three options: 1) use site-specific biomass values determined by field inventory; 2) use direct measurements of annual carbon fluxes using eddy-covariance techniques; or 3) employ an appropriate Tier 3 model. We believe that for major mining projects with large footprints, a combination of these approaches will be required, i.e., deployment of a Tier 3 model with validation of model predictions from field inventory and direct measurement of carbon fluxes on key instrumented sites through use of eddy-covariance techniques.

- Use of empirical measurements as an alternative to modelling will require substantial time and resources, and additionally require years of monitoring to reach reliable conclusions on long-term performance. Although we do not advocate for use of empirical measurements as the primary approach to ecosystem carbon accounting for mine-reclamation projects, they will almost certainly be required to validate model predictions.
- Both empirical measurements and default-value approaches have limitations with respect to their support of analysis of different development and reclamation scenarios and sensitivities. It is likely that, for major mines, EMLI will want to evaluate different "what-if" scenarios for mine development and reclamation. This evaluation will require use of a relatively detailed model with parameterization for mine-reclamation conditions.

Table 3. Default values of age and living biomass of leading forest species at maximum carrying capacity (MCC) for British Columbia. MCC is defined as the age when the growth of above-ground biomass reaches a plateau. Table modified from Environment and Climate Change Canada (2021a).

Ecozone[a]	Species	Site index[b]	Age at MCC	Live biomass at MCC (t C ha^{-1})
TP	lodgepole pine	5.0 to 14.9	151	108
TP	lodgepole pine	15.0 to 24.9	130	127
TP	lodgepole pine	25.0 to 34.9	128	175
TP	black spruce	5.0 to 14.9	186	92
TP	black spruce	15.0 to 24.9	160	16
TP	black spruce	15.0 to 34.9	140	268
BP	lodgepole pine	5.0 to 14.9	160	94
BP	lodgepole pine	15.0 to 24.9	141	130
BP	lodgepole pine	25.0 to 34.9	128	182
BP	black spruce	5.0 to 14.9	185	101
BP	black spruce	15.0 to 24.9	158	107
BP	black spruce	25.0 to 34.9	139	261
BC	lodgepole pine	5.0 to 14.9	160	103
BC	lodgepole pine	15.0 to 24.9	142	145
BC	lodgepole pine	25.0 to 34.9	126	195
BC	black spruce	5.0 to 14.9	186	113
BC	black spruce	15.0 to 24.9	158	195
BC	pine	10.0 to 14.9	137	283
PM	lodgepole pine	15.0 to 24.9	205	149
PM	lodgepole pine	15.0 to 24.9	200	290
PM	lodgepole pine	15.0 to 24.9	195	421
PM	lodgepole pine	15.0 to 34.9	160	460
MC	lodgepole pine	5.0 to 14.9	188	92
MC	lodgepole pine	15.0 to 24.9	171	139
MC	lodgepole pine	25.0 to 34.9	151	191
MC	lodgepole pine	15 to 24.9	167	143
MC	lodgepole pine	25.0 to 34.9	154	203
MC	lodgepole pine	0 to 5	190	35

[a] Terrestrial Ecozones of Canada present in British Columbia are: Boreal Cordillera (BC), Boreal Plains (BP), Montane Cordillera (MC), Pacific Maritimes (PM), and Taiga Plains (TP).

[b] Site index is an estimate of potential productivity, based on the measured or projected height (m) of the 100 largest trees per ha at a breast-height age of 50 years.

5.2. MODEL SELECTION

Our review of various modelling approaches for ecosystem carbon accounting suggests that the CBM-CFS3 (or the related GCBM) is a clear front-runner for use in mine-reclamation projects in BC. It has been robustly developed for forest ecosystems in the province, and has the architecture required to allow for the evaluation of reclamation scenarios. Its primary limitations are shared by other reviewed models, at least for boreal and temperate forest ecosystems in BC and, specifically for GCBM, the absence of a graphical user interface requires users to have programming knowledge to operate it. As noted above, there are barriers to immediate and meaningful use of the CBM-CFS3 with respect to mine reclamation in BC, principally the fact that the model is not explicitly parameterized for starting conditions (SOM) for reclamation-cover systems, and that it is not developed for wetlands or grasslands. Some options for addressing these limitations are discussed in the Recommendations section.

5.3. APPLICATION OF THE CBM-CFS3 FOR MINE RECLAMATION IN BC

Despite the limitations discussed above, the CBM-CFS3 can be used to evaluate mine-reclamation scenarios. We ran the model using simplified assumptions about mine reclamation to illustrate this potential (Figure 2 and Figure 3). Assumptions for our model runs were as follows:

- A hypothetical proposed mine footprint of 1000 ha in the Montane Cordillera ecozone, currently occupied by a 50-year-old, fire-origin stand of lodgepole pine with an assumed growth curve.
- Model simulations were conducted for a period of 200 years, to explore the dynamics of not only reclamation but transition to post-mining land uses (in this case, forest harvest).[16] The baseline condition is labelled "non-mine" in Figure 2 and Figure 3, and assumes that the current stand is not cleared for mining, but continues to grow until a rotation age of 80 (Year 30 in the simulations), at which point it is logged (with non-merchantable above-ground biomass burned) and reforested. Given 80-year rotations, this baseline stand is logged in model Years 30, 110, and 190.

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[16] The CBM-CFS3 User's Guide (Kull et al. 2019) states, "The model works in annual time steps. It is not possible to simulate time steps of less than 1 year. Research applications of the model have simulated periods extending over several centuries, but for most applications shorter simulation periods are more appropriate."

- Three reclamation scenarios were modelled:
  1. A reclamation-cover system with a relatively high initial soil organic matter (SOM) content[17] and the same growth rate as the baseline stand;
  2. A reclamation-cover system with a relatively low initial SOM content[18] and the same growth rate as the baseline stand; and
  3. A reclamation cover system with a relatively low initial SOM content and a growth rate reduced by 15% from that of the baseline stand.

  Reclamation scenarios were run assuming that mining occurs over 30 years (model years 0-29), and that revegetation of the entire 1000-ha footprint occurs in model Year 30. Following reclamation, resulting stands were treated identically to the baseline stand, i.e., they are logged every 80 years with non-merchantable above-ground biomass burned.

Results of these simulations are presented for stocks (total ecosystem carbon) in Figure 2 and fluxes (ecosystem carbon assimilation rate) in Figure 3.[19] Summaries of these results are:

- Stocks—reclamation scenarios have substantially lower carbon stocks than baseline, as they do not start with residual biomass. They assimilate carbon relatively quickly, but by the end of the first rotation still have values roughly 13-23% lower than the baseline scenario. In subsequent rotations the reclamation-origin stands become closer to baseline conditions, but it will take multiple rotations to reach equivalency. Based on stocks, reclamation stands do not achieve ecosystem carbon equivalency. Carbon stocks in reclaimed stands in these scenarios appear to be sensitive to both assumptions with respect to SOM content of reclamation covers and to growth rates of reclaimed forests.
- Fluxes—reclamation scenarios show greater net ecosystem assimilation, likely due to the relative lack of decomposition and respiration in the new reclaimed ecosystems in comparison to the baseline forest. Modelled reclamation fluxes are within the range of fluxes measured by eddy covariance as discussed in Section 3.3.1.

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[17] The high-SOM soil was modelled using CBM-CFS3's default assumptions for a Brunisolic soil type, which is 83 t ha^{-1} carbon. Assuming that that carbon is largely located in the upper 25 cm of the soil profile, this would equate to an organic-matter content of approximately 4% (gravimetric, assuming a whole-soil bulk density of 1500 kg/m^3).

[18] The low-SOM soil was modelled using CBM-CFS3's default assumptions for a Luvisolic (western Canada) soil type, which is 66 t ha^{-1} carbon. Assuming that that carbon is largely located in the upper 25 cm of the soil profile, this would equate to an organic-matter content of approximately 3% (gravimetric, assuming a whole-soil bulk density of 1500 kg/m^3). In the current CBM-CFS3 configuration, these values could be edited to reflect initial values for a reclamation cover system.

[19] Values displayed in figures are in units of Mg C for the 1000-ha simulated area. Therefore, to estimate units in Mg C ha^{-1}, divide values by 1000.

These results are not meant to support actual conclusions on mine-reclamation outcomes on carbon dynamics, but simply to illustrate the applicability of the CBM-CFS3 to mine-reclamation scenarios.

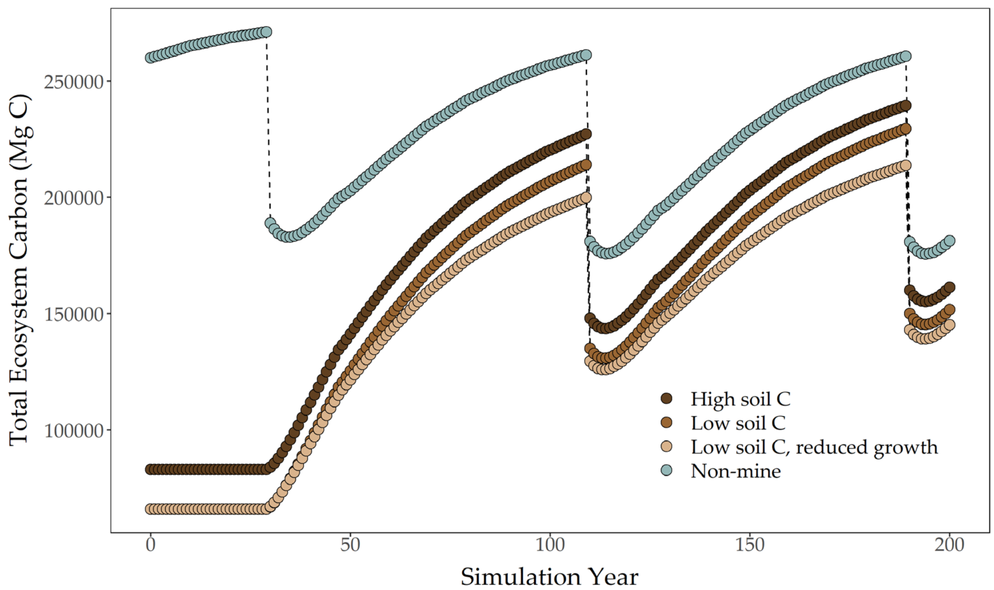

Figure 2. Total ecosystem carbon (C) estimated over time by CBM-CFS3 for lodgepole-pine stands in BC under reclamation scenarios with initially high soil C, initially low soil C, and initially low soil C with reduced growth, and a non-mined, forested scenario. Each simulation is for an area of 1000 ha.

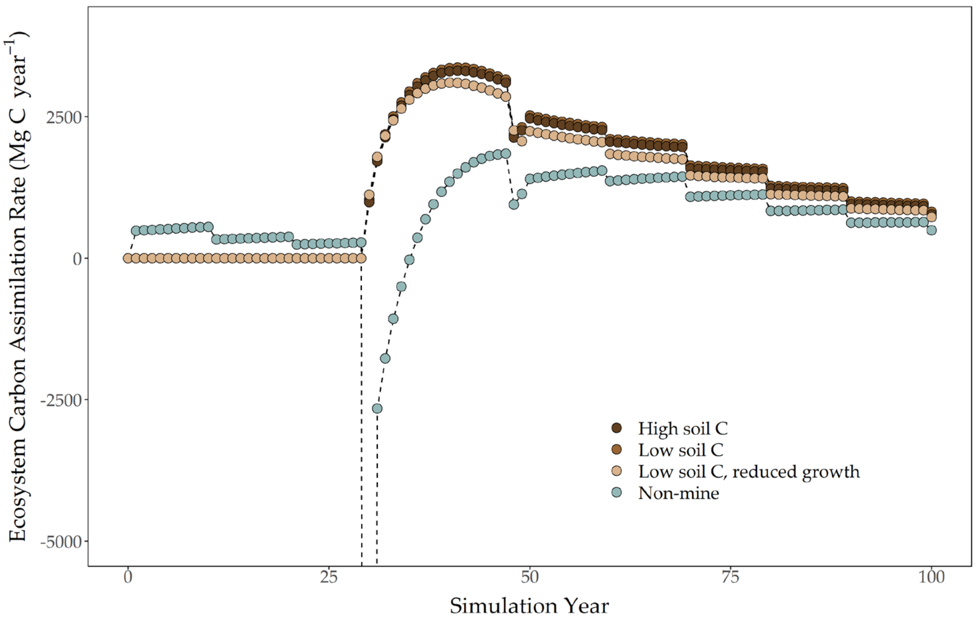

Figure 3. Ecosystem carbon (C) assimilation rates over time estimated by CBM-CFS3 for lodgepole-pine stands in BC under reclamation scenarios with initially high soil C, initially low soil C, and initially low soil C with reduced growth, and a non-mined, forested scenario. Each simulation is for an area of 1000 ha. Carbon assimilation rates not shown in the graph range from -70,000 to -85,000 Mg C year^{-1}.[20]

[20] Non-smoothed lines in the graph are due to decadal adjustments of some carbon parameters tracked by the CBM-CFS3.

This illustrated approach could be used as the basis for generating comparisons for evaluation of equivalent capability. A simplified, quantitative version of this comparison is shown in Table 4, based on the CBM-CFS3 modelling discussed above. This comparison assumes stocks and fluxes from Figure 2 and Figure 3, and also assumes the loss of 200 ha of the ecosystem to a non-reclaimed or non-terrestrial footprint such as pit lakes or reclamation-exempt pit walls.

Table 4. Illustration of a comparison of equivalent capability in a mine-reclamation scenario. Post-mine stocks and fluxes are assessed in simulation year 80, 50 years after reclamation. The baseline carbon (C) flux is assessed in the same year for a modelled stand assuming that mining did not occur.

Ecosystem type	Pre-mine area (ha)	Pre-mine C stocks (Mg)	Baseline annual C assimilation (Mg)	Post-mine area (ha)	Post-mine C stocks (Mg)	Post-mine annual C assimilation (Mg)
Lodgepole pine	1000	260,000	835	800	148,000	1,024

5.4. CARBON ASSIMILATION IN MINE RECLAMATION

The primary strategies to promote carbon retention and assimilation for mine development and reclamation involve:

- maximizing retention (i.e., non-disturbance) of carbon-rich ecosystems, such as organic wetlands;
- maximizing retention of soils, which have substantial SOM pools;[21]
- maximizing retention of non-merchantable biomass, and minimizing burning of this biomass as part of clearing operations; and
- application of additional organic amendments to increase the carbon content of soils.

These options should follow standard mitigation-hierarchy approaches, i.e., avoidance of disturbance should be maximized, followed by minimizing disturbance and maximizing retention of soils and biomass, followed by application of organic amendments. Maximizing retention of non-merchantable biomass would bring the reclamation-scenario carbon stocks modelled in Figure 2 closer to baseline conditions.

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[21] It could be argued that retention of organic wetlands and soils is not a net carbon benefit in comparison to burying these ecosystems/materials under mining disturbances, as in both scenarios the carbon may be sequestered.

As discussed above, there may be some tension between goals of maximizing carbon assimilation through techniques such as application of organic amendments and intensive cropping of species such as willows and those of meeting biodiversity targets. There has been very little research to date in BC on reclaiming native-ecosystems with high-nutrient amendments, and some native ecosystems with high biodiversity value (e.g., stands of white bark pine) may have relatively low carbon-assimilation rates.

5.5. CLIMATE-CHANGE CONSIDERATIONS

BC has some robust tools to support quantitative consideration of changing climate in mine reclamation. These include the ClimateBC tool and related products such as the CCISS Tool and IEG's QEA model. These tools allow users to estimate current and future climate and water-balance parameters based on our understanding of changing climate, to estimate ecosystem occurrence based on climate and characteristics of reclamation sites and materials, and to select appropriate overstory species for reclamation. The CBST Seedlot Selection Tool allows users to find appropriate seedlots (for propagation of seedlings for use in reclamation programs) based on the location and climate of their reclamation site and current/expected climate changes. Used in concert with the various BEC regional field guides, reclamation ecologists also have access to information on appropriate understory species.

The rate of climate change in BC presents challenges to the concept of equivalent capability, as historical or current conditions in pre-mine-development settings may not have persisted or be expected to persist even if the mine was not developed. Another way of looking at this is that, due to climate change, there is no static baseline against which to measure achievement of equivalency. An important concept that can help address these challenges is use of a "climate-shifted baseline", in which climate models are used to estimate the ecosystems that would have occurred in a mine area in the event that mining did or does not proceed. This climate-shifted baseline can be estimated using the ClimateBC tool (for shifting BEC subzones and variants) and IEG's QEA model (for site series within BEC subzones/variants), or other quantitative approach that allows estimation of edatopic position based on reclamation materials, topography, and climate. Use of a climate-shifted baseline allows for an equivalency comparison for ecosystems (using the approach described above), for end land use capabilities such as wildlife habitat (by using habitat-capability modelling applied to climate-shifted-baseline ecosystems), and even for ecosystem carbon accounting, as climate change is incorporated into the CBM-CFS3 tool.

5.6. RECOMMENDATIONS

Recommendations are provided below by topic area.

5.6.1. Climate change

Although there has been little substantial and widespread effort to incorporate climate-change planning into mine reclamation in BC, some useful tools are freely available to support this effort. We recommend that EMLI consider the following:

- Instruct proponents to include explicit, specific, and quantitative considerations of climate change in their reclamation planning, including demonstration of how this has been done.
- Instruct proponents to use available BC government or other public tools such as ClimateBC, CCISS, and the CBST Seedlot Selection Tool, as updated, or other tools as they become available. For reforestation, proponents should show revegetation options based on CCISS, and discuss any rationale for not following these options.
- Instruct proponents to use a quantitative approach to estimating site-series occurrence through ecohydrological modelling in current or future reclamation areas affected by climate change. IEG's QEA tool is freely available and one option to address this instruction, but proponents should be able to use any approach to achieve this objective, as long as they can demonstrate that the approach is rigorous.[22]
- Instruct proponents to present information on use of a climate-shifted baseline for assessment of achievement of equivalent capability.

These recommendations do not cover design of surface-water conveyance features and pit lakes. For the former, it is our understanding that hydrologists and engineers are already incorporating climate-change considerations into their development of key design parameters such as storm return intervals and probable maximum floods. For the latter, we lack sufficient expertise to provide comment on how planning for climate change should be incorporated into pit-lake management and reclamation, other than in terms of hydrology and water-balance modelling.

[22] IEG's QEA tool runs on the Shiny App, like the CCISS tool. We are open to developing this tool to a similar level as CCISS in terms of function and user interface, but that requires more resources than IEG can currently allocate internally, and would need additional support.

5.6.2. Ecosystem carbon accounting

We recommend that EMLI adopt, and adapt if necessary, the SACC decision tree (Figure 1) for ecosystem carbon accounting approach based on project size and ecosystem characteristics. For larger sites or sites with a high proportion of carbon-rich ecosystems, deployment of a Tier 3 model is required, and we recommend that that model be the CBM-CFS3 or GCBM.

We have considered two broad approaches to use of the CBM-CFS3/GCBM for mine-reclamation projects in BC, as follows:

1. **Independent development**—instruct proponents to use the CBM-CFS3/GCBM to evaluate baseline and reclamation conditions, and provide comparisons of equivalency and of the expected outcomes of different reclamation approaches, and let proponents find appropriate internal and/or external experts to do this work. The substantial disadvantage of this approach is that current personnel with expertise in the CBM-CFS3/GCBM, and more generally in ecosystem carbon accounting, are not the same as those personnel with expertise in mine reclamation. This difference is likely to either result in relatively proficient deployment of the CBM-CFS3/GCBM with possibly poorly informed reclamation scenarios, or deployment of the CBM-CFS3/GCBM by personnel with a good understanding of mine reclamation, but who may not fully understand the nuances of the CBM-CFS3/GCBM.[23]
2. **Focussed development**—allocate resources to further development of the CBM-CFS3/GCBM to be better suited for mine reclamation, including parameterization for characteristics of reclamation-cover systems, for variable retention of non-merchantable, above-ground biomass, and for growth curves applicable to mine reclamation in BC. The Canadian Forest Service has expressed interest in participating in this approach, and this would likely be the most cost-effective allocation of resources: to support a small group of people with expertise in the CBM-CFS3/GCBM to work alongside a small group with expertise in mine reclamation, to develop the capability of the CBM-CFS3/GCBM to be used as a Tier 3 ecosystem carbon accounting model for management of mine development and reclamation in BC.

One initial step in the focussed-development approach would be to convene a facilitated workshop with subject-matter experts in mine reclamation and ecosystem carbon accounting, including the CBM-CFS3/GCBM. Objectives and intended outcomes of the workshop would

[23] A possible alternative is that some consultancies would develop the skills or form partnerships to conduct this task well, but it is likely that this capacity would be relatively limited, including within EMLI's staff.

need to be clearly articulated beforehand, with preparatory work done by participants. The workshop could address key issues such as how to approach:

- modelling afforestation of reclamation-cover systems in CBM-CFS3/GCBM;
- modelling of variable retention of biomass;
- modelling of non-forest ecosystems of important carbon and biodiversity value such as grasslands and wetlands;
- development of growth curves for reclamation sites and future climate-change scenarios;
- conducting sensitivity and uncertainty analyses to identify focus areas for further work;
- modelling of use of organic residuals for high-carbon-assimilation scenarios; and
- deployment of the CBM-CFS3/GCBM for mine reclamation.
- For larger sites or sites with a high proportion of carbon-rich ecosystems where CBM-CFS3/GCBM is deployed, we recommend that proponents be instructed to validate model assessments over time using empirical measurements from developing reclamation sites and/or direct measurement of carbon fluxes using eddy-covariance and related techniques, such as correlation of remote sensing with eddy covariance data. These approaches could also be used prior to modelling, to build knowledge and data on ecosystem carbon assimilation in BC. For instance, although eddy-covariance techniques have been used to measure carbon fluxes in reclaimed ecosystems, to our knowledge they have not been applied in BC. In addition, forensic/retrospective studies such as that reported by Metsaranta et al. (2018) could be used to help parameterize the CBM-CFS3/GCBM for use in mine reclamation in BC, and better understand carbon exchanges in reclaimed ecosystems in a range of BC climates. There are a number of candidate areas for such work, but a primary location could be the C Spoil forest at Fording River. This forest consists of hybrid spruce and lodgepole pine planted on coal mine rock in the mid 1980s that has now formed a closed-canopy forest.

5.6.3. Carbon sequestration

We recommend that EMLI guidance on techniques in reclamation to enhance carbon assimilation should follow initial assessment of ecosystem carbon changes resulting from mining. That is, by presenting information on a comparison of pre-development/baseline and reclamation carbon stocks and fluxes, proponents should be able to identify factors affecting ecosystem carbon in reclamation, and attendant mitigations. We believe that this probably needs to occur on a site-specific basis, as different effects or conversions may be driving carbon losses (e.g., wetland or grassland loss), and as potential mitigations need to be balanced against other commitments such as protection of species at risk and other biodiversity objectives.

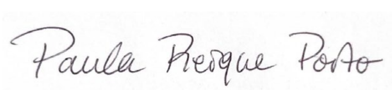
One area for potential further development would be the parameterization for the CBM-CFS3 tool as discussed above to account for variable retention of non-merchantable above-ground biomass (i.e., woody debris) and use of other organic residuals in mine reclamation, and to validate this parameterization with site-specific research.

6. CLOSURE

This report has been prepared by the authors and Qualified Professionals listed below. We trust the report satisfies your requirements at this time. Please do not hesitate to contact us if you have any questions or comments.

Justin Straker, MSc, PAg (BC, AB, SK, ON)
Soil Scientist, Forest Ecologist

Role: report preparation and review;
responsible Qualified Professional



Paula Porto, B.Sc., A.Ag.
Soil Scientist, Data Analyst

Role: literature review and jurisdictional scan
and report preparation.

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APPENDIX A — ANNOTATED BIBLIOGRAPHY

Table A-1. Brief descriptions of all reviewed documents.

Reference	Topic	Description
Akala, V. A., & Lal, R. (2001). Soil organic carbon pools and sequestration rates in reclaimed mine soils in Ohio. Journal of Environmental Quality, 30(6), 2098–2104. https://doi.org/10.2134/jeq2001.2098	Carbon sequestration	Peer-reviewed paper using a chronosequence study to investigate the impact of four treatments (pasture and forest with and without topsoil application) on the soil carbon pool at a coal mine in Ohio.
Alam, M. S., Barbour, S. L., Elshorbagy, A., & Huang, M. (2018). The impact of climate change on the water balance of oil sands reclamation covers and natural soil profiles. Journal of Hydrometeorology, 19(11), 1731–1752. https://doi.org/10.1175/JHM-D-17-0230.1	Climate change	Peer-reviewed paper showing the projection of the hydrology of two reclamation sites at an oil-sands mine in Alberta using a water balance model with baseline and future climate data for three relative concentration pathways (RCPs).
Anderson, J., Baker, T., Krebs, V., McMahen, K., Porto, P., Ryan, M., & Straker, J. (2022). Characterization of soils, vegetation, and water and carbon fluxes at instrumented sites at Faro mine, 2021. Prepared for SRK Consulting.	Carbon sequestration	Report by Integral Ecology Group (IEG) describing carbon fluxes from tailings at a closed lead-zinc mine in the Yukon territory.
Antonelli, P. M., Fraser, L. H., Gardner, W. C., Broersma, K., Karakatsoulis, J., & Phillips, M. E. (2018). Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation. Ecological Engineering, 117, 38–49. https://doi.org/10.1016/j.ecoleng.2018.04.001	Carbon sequestration	Peer-reviewed paper investigating the impact of a one-time biosolids application on soil carbon and plant biomass on reclaimed tailings at a copper and molybdenum mine, 13 years after the biosolids application.
Australian Government. (2022). National Inventory Report 2020: the Australian government submission to the United Nations Framework Convention on Climate Change (Volume 2). https://unfccc.int/documents/478957	Carbon modelling	Methodology volume of the Australian National Inventory Report describing how the Full Carbon Accounting Model (FullCAM) is used to estimate changes to carbon stocks for the Land Use, Land Use Change, and Foresty (LULUCF) sector of their national GHG inventory.

Reference	Topic	Description
Baker, T., Ryan, M., & Straker, J. (2021). User guide for the quantitative ecohydrological analysis tool for mine reclamation.	Climate change	User guide for the Quantitative Ecohydrological Analysis (QEA) tool, which predicts ecological classification parameters within BC's Biogeoclimatic Ecosystem Classification (BEC) system and water-balance parameters based on the combination of soil characteristics, topography, and location-specific climate data obtained from ClimateNA/BC for historical, current, and future time periods.
Bona, K. A., Shaw, C., Thompson, D. K., Hararuk, O., Webster, K., Zhang, G., Voicu, M., & Kurz, W. A. (2020). The Canadian model for peatlands (CaMP): A peatland carbon model for national greenhouse gas reporting. *Ecological Modelling*, *431*. https://doi.org/10.1016/j.ecolmodel.2020.109164	Carbon modelling	Peer-reviewed paper introducing a model framework for estimating greenhouse gas (GHG) fluxes for Canadian peatlands using the Canadian Model for Peatlands (CaMP), which can be used as a submodule of the Generic Carbon Budget Model (GCBM).
Botula, Y. D., Guittonny, M., Bussière, B., & Bresson. (2019). Will tree colonisation increase the risks of serious performance loss of engineered covers under climate change in Québec, Canada? *Proceedings of the International Conference on Mine Closure*, *2019-September*, 607–620. https://doi.org/10.36487/ACG_rep/1915_49_Botula	Climate change	Conference paper discussing the impact of shifting species distributions due to climate change on the performance of engineered covers at a copper and nickel mine in Québec.
Chen, J., Colombo, S. J., Ter-Mikaelian, M. T., & Heath, L. S. (2010). Carbon budget of Ontario's managed forests and harvested wood products, 2001-2100. *Forest Ecology and Management*, *259*(8), 1385–1398. https://doi.org/10.1016/j.foreco.2010.01.007	Carbon modelling	Peer-reviewed paper describing the modelling of forest carbon stocks between 2001 and 2100 in Ontario using a version of the Forest Carbon Budget Model, FORCARB-ON.
Clark, M. G., Humphreys, E., & Carey, S. K. (2019). The initial three years of carbon dioxide exchange between the atmosphere and a reclaimed oil sand wetland. *Ecological Engineering*, *135*, 116–126. https://doi.org/10.1016/j.ecoleng.2019.05.016	Carbon sequestration	Peer-reviewed paper measuring CO_2 fluxes at a constructed wetland reclamation project on an oil-sands mine in Alberta.

Reference	Topic	Description
Eggleston, S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 4: Agriculture, forestry and other land use.* https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html	Carbon modelling	Introductory chapter of the Agriculture, Forestry, Other Land Use volume of the 2006 IPCC Guideline for National Greenhouse Gas Inventories report. Includes an explanation of tiered approaches.
Environment and Climate Change Canada. (2021a). *Draft technical guide related to the strategic assessment of climate change: guidance on quantification of net GHG emissions, impact on carbon sinks, mitigation measures, net-zero plan and upstream GHG assessment*.	Carbon modelling	Draft technical guide for the Strategic Assessment on Climate Change. This report outlines accepted approaches for proponents estimating net GHG emissions and impacts on carbon sinks from their projects.
Environment and Climate Change Canada. (2021b). *National Inventory Report 1990-2019: Greenhouse Gas Sources and Sinks in Canada (Part 2).*	Climate change	Methodology chapter of the Canadian National Inventory Report for the 1990-2019 period.
Gaboury, S., Boucher, J. F., Villeneuve, C., Lord, D., & Gagnon, R. (2009). Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Québec's closed-crown boreal forest. *Forest Ecology and Management*, *257*(2), 483–494. https://doi.org/10.1016/j.foreco.2008.09.037	Carbon modelling	Peer-reviewed paper using the CO2FIX model to estimate the carbon balance of a baseline boreal forest and an afforestation scenario in Quebec.
Ghosh, D., & Maiti, S. K. (2021). Eco-restoration of coal mine spoil: biochar application and carbon sequestration for achieving UN sustainable development goals 13 and 15. *Land*, *10*(11). https://doi.org/10.3390/land10111112	Carbon sequestration	Peer-reviewed paper investigating the effect of applying two rates of biochar made from an invasive species to an afforested mine spoil in a coal mine in India.
Heath, L. S., Nichols, M. C., Smith, J. E., & Mills, J. R. (2010). *FORCARB2: an updated version of the U.S. Forest Carbon Budget Model*. http://nrs.fs.fed.us/pubs/35613.	Carbon modelling	User guide of the Forest Carbon Budget Model (FORCARB2).
Kim, H., Kim, Y. H., Kim, R., & Park, H. (2015). Reviews of forest carbon dynamics models that use empirical yield curves: CBM-CFS3, CO2FIX, CASMOFOR, EFISCEN. In *Forest Science and Technology* (Vol. 11, Issue 4, pp. 212–222). Taylor and Francis Ltd. https://doi.org/10.1080/21580103.2014.987325	Carbon modelling	Peer-reviewed paper comparing four forest carbon models that use empirical yield curves (CBM-CFS3, CO2FIX, CASMOFOR, and EFISCEN).

Reference	Topic	Description
Kull, S. J., Rampley, G. J., Morken, S., Metsaranta, J., Neilson, E. T., & Kurz, W. A. (2019). *Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) version 1.2: user's guide*. https://d1ied5g1xfgpx8.cloudfront.net/pdfs/39768.pdf	Carbon modelling	User guide for the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3).
Kurz, W. A., Dymond, C. C., White, T. M., Stinson, G., Shaw, C. H., Rampley, G. J., Smyth, C., Simpson, B. N., Neilson, E. T., Trofymow, J. A., Metsaranta, J., & Apps, M. J. (2009). CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling, 220(4), 480–504. https://doi.org/10.1016/j.ecolmodel.2008.10.018	Carbon modelling	Peer-reviewed paper describing the updates to the CBM-CFS3 up to 2009 and how certain outputs were validated with empirical data.
MacKenzie, W. H., & Mahony, C. R. (2021). An ecological approach to climate change-informed tree species selection for reforestation. *Forest Ecology and Management*, *481*. https://doi.org/10.1016/j.foreco.2020.118705	Climate change	Peer-reviewed paper introducing the climate-change informed species selection (CCISS) tool, which provides spatially explicit feasibility ratings by tree species and BEC site series based on climate data for historic, current, and future time periods.
Ménard, I., Thiffault, E., Boulanger, Y., & Boucher, J. F. (2022). Multi-model approach to integrate climate change impact on carbon sequestration potential of afforestation scenarios in Quebec, Canada. *Ecological Modelling*, *473*. https://doi.org/10.1016/j.ecolmodel.2022.110144	Carbon modelling	Peer-reviewed paper using a forest gap model (PICUS) to create growth curves for three RCPs (2.6, 4.5, and 8.5), which were then used with CBM-CFS3 to estimate carbon dynamics of different afforestation scenarios in Quebec.
Metsaranta, J. M., Beauchemin, S., Langley, S., Tisch, B., & Dale, P. (2018). Assessing the long-term ecosystem productivity benefits and potential impacts of forests re-established on a mine tailings site. *Forests*, *9*(11). https://doi.org/10.3390/f9110707	Carbon modelling	Peer-reviewed paper using a hybrid biometric modelling approach to generate inputs to CBM-CFS3 to evaluate the carbon dynamics of pine plantations at a copper-nickel mine in Ontario.
Ministry of Environment and Climate Change Strategy. (2022). *Methodology report for the British Columbia provincial inventory of greenhouse gas emissions 1990-2020*.	Carbon modelling	Report describing the methodology used for British Columbia's inventory of GHG emissions between 1990 and 2020. The province uses the same methodology as the national inventory report, with few exceptions which are outlined in the report.

Reference	Topic	Description
Misebo, A. M., Pietrzykowski, M., & Woś, B. (2022). Soil carbon sequestration in novel ecosystems at post-mine sites—a new insight into the determination of key factors in the restoration of terrestrial ecosystems. Forests, 13(1). https://doi.org/10.3390/f13010063	Carbon sequestration	Peer-reviewed paper outlining approaches to enhancing carbon sequestration in reclaimed mine soils.
Nicholls, D. (2022). Chief Forester's standards for seed use. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/tree-seed/legislation-standards/current-standards/consolidated_cf_stds__amended_1apr2022.pdf	Climate change	Report outlining standards for the storage, selection, use, and transfer of registered lots, and for the registration of seedlots and vegetative lots used to establish stands under section 29 of the Forest and Range Practices Act. Includes standards for climate-based seed transfer.
Nenzén, H. K., Price, D. T., Boulanger, Y., Taylor, A. R., Cyr, D., & Campbell, E. (2020). Projected climate change effects on Alberta's boreal forests imply future challenges for oil sands reclamation. *Restoration Ecology*, *28*(1), 39–50. https://doi.org/10.1111/rec.13051	Climate change	Peer-reviewed paper outlining the use of a landscape model (LANDIS-II) to simulate the response of boreal forests to climate change and disturbances in the Alberta oil-sands region.
Petelina, E., Klyashtorin, A., & Yankovich, T. (2014). Field trials on use of biochar versus peat for land reclamation purposes. *British Columbia Mine Reclamation Symposium*, 1–11.	Carbon sequestration	Conference paper describing the impact of peat and biochar applications on the vegetation cover of a perennial seed mix at a uranium mine in Saskatchewan.
Pietrzykowski, M., Gruba, P., & Sproull, G. (2017). The effectiveness of Yellow lupine (Lupinus luteus L.) green manure cropping in sand mine cast reclamation. *Ecological Engineering*, *102*, 72–79. https://doi.org/10.1016/j.ecoleng.2017.01.026	Carbon sequestration	Peer-reviewed paper describing a chronosequence study to assess the use of yellow lupine as a green manure crop prior to reforestation of opencast sand mining sites in Poland.
Pinkard, E. A., Paul, K., Battaglia, M., & Bruce, J. (2014). Vulnerability of plantation carbon stocks to defoliation under current and future climates. Forests, 5(6), 1224–1242. https://doi.org/10.3390/f5061224	Carbon modelling	Peer-reviewed paper estimating future carbon stocks of a eucalyptus plantation with FullCAM. The authors used an insect damage model and a biomass productivity model to create annual biomass estimates from future climate scenarios for input into FullCAM.

Reference	Topic	Description
Rissik, D., & Iles, M. (2022). Climate change and mine closure: initial risk assessment of the Ranger Mine closure plan. *Proceedings of the International Conference on Mine Closure*, *1*, 603–612. https://doi.org/10.36487/ACG_repo/2215_42	Climate change	Conference paper outlining the climate change risk assessment of a closure plan for a uranium mine in Australia.
Rooney, R. C., Robinson, D. T., & Petrone, R. (2015). Megaproject reclamation and climate change. *Nature Climate Change*, *5*, 963–966.	Climate change	Commentary paper outlining a framework to improve the success of large reclamation projects in a changing climate. The framework is based on the reference condition approach and bioclimate envelope models.
Savage, R. J., Pearce, S., Mueller, S., Barnes, A., Renforth, P., & Sapsford, D. (2019). Methods for assessing acid and metalliferous drainage mitigation and carbon sequestration in mine waste: A case study from Kevitsa mine, Finland. *Proceedings of the International Conference on Mine Closure*, *2019-September*, 1073–1086. https://doi.org/10.36487/ACG_rep/1915_86_Savage	Carbon sequestration	Conference paper assessing the potential for carbon sequestration and the mitigation of acid mine drainage with alkaline by-products from the carbonation process at a Finnish nickel mine.
Schelhaas, M. J. , van Esch, P. W. , de Jong, B. H. J. , Kanninen, M. , Liski, J. , Masera, O. , Mohren, G. M. J. , Nabuurs, G. J. , Palosuo, T. , Pedroni, L. , Vallejo, A. , & Vilen, T. (2004). *CO2FIX V 3.1-A modelling framework for quantifying carbon sequestration in forest ecosystems*.	Climate change	Commentary paper outlining a framework (based on the reference condition approach and bioclimate envelope models) to improve the success of large reclamation projects in a changing climate.
Shaw, C. H., Rodrigue, S., Voicu, M. F., Latifovic, R., Pouliot, D., Hayne, S., Fellows, M., & Kurz, W. A. (2021). Cumulative effects of natural and anthropogenic disturbances on the forest carbon balance in the oil sands region of Alberta, Canada; a pilot study (1985–2012). *Carbon Balance and Management*, *16*(1). https://doi.org/10.1186/s13021-020-00164-1	Carbon modelling	Peer-reviewed paper using the Generic Carbon Budget Model (GCBM) to simulate carbon dynamics in 1.3 million ha of upland forest in the oil-sands region of Alberta, experiencing both anthropogenic (forestry, energy sector) and natural (wildfire, insect) disturbances.
Shrestha, R. K., & Lal, R. (2006). Ecosystem carbon budgeting and soil carbon sequestration in reclaimed mine soil. *Environment International*, *32*(6), 781–796. https://doi.org/10.1016/j.envint.2006.05.001	Carbon sequestration	Peer-reviewed paper outlining, among other things, the mechanisms of soil organic carbon sequestration and stabilization, and factors impacting carbon sequestration potential in reclaimed mine soil ecosystems.

Reference	Topic	Description
Shrestha, R. K., Lal, R., & Jacinthe, P.-A. (2009). Enhancing carbon and nitrogen sequestration in reclaimed soils through organic amendments and chiseling. *Soil Science Society of America Journal*, *73*(3), 1004–1011. https://doi.org/10.2136/sssaj2008.0216	Carbon sequestration	Peer-reviewed paper investigating the impact of chiseling and different amendments (cow manure and lime, straw mulch and NPK) on soil and biomass carbon stocks at a coal mine in Ohio.
Somogyi, Z. (2016). Projected effects of climate change on the carbon stocks of European beech (Fagus sylvatica L.) forests in Zala County, Hungary. Lesnicky Casopis Forestry Journal, 62(1), 3–14. www.scientia.hu/casmofor	Carbon modelling	Peer-reviewed study estimating carbon losses from climate change-driven extinction of European beech using CASMOFOR and extinction mortality rates acquired from a separate study.
Somogyi, Z. (2019, July 13). *CASMOFOR: Carbon Sequestration Model for Forestations - an accounting model to assess the removals and emissions of carbon by afforestations*. http://www.scientia.hu/casmofor/indexE.php	Carbon modelling	Website for the Carbon Sequestration Model for Forestations (CASMOFOR) providing information on model structure, example model outputs, and links for model download.
Straker, J. R., Carey, S. K., Petrone, R. M., Baker, T. D., & Strilesky, S. L. (2019). *Developing a functional approach to assessment of land capability: utilizing ecosystem water and carbon nutrient fluxes as integrated measures of reclamation performance*.	Carbon sequestration	Report synthesizing 15 years of research on water use, carbon assimilation, and associated ecosystem development on reclaimed oil-sands mine sites and non-mine reference sites to identify indicators of ecosystem function useful for evaluating land capability on reclaimed sites.
Ter-Mikaelian, M. T., Chen, J., & Colombo, S. J. (2022). Duration of climate change mitigation benefits from increasing boreal forest harvest age by 10 years. *Forests*, *13*(8). https://doi.org/10.3390/f13081279	Carbon modelling	Peer-reviewed paper investigating the duration of the climate change mitigation benefit of increasing forest harvest age. The authors modelled carbon stocks of boreal forests in Ontario using a mix of newly developed equations and equations from FORCARB-ON2.
Teshima, M. A., & Lavery, J. M. (2022). Beneficial use of municipal biosolids in mine reclamation to achieve a narrative of layered co-benefits for mines and municipal biosolids generators. *British Columbia Technical and Research Committee on Reclamation*, 1–9.	Carbon sequestration	Conference paper introducing a reclamation project that integrates biosolids application with the establishment of large-scale willow plantations at a coal mine in Alberta.

Reference	Topic	Description
Trlica, A., & Teshima, M. (2011). *Assessing soil carbon storage and climate change mitigation in biosolids mine reclamation projects* (British Columbia Mine Reclamation Symposium, Ed.).	Carbon sequestration	Conference paper comparing the carbon stocks in biosolids-amended versus conventionally reclaimed soils at five closed mines in BC, Washington, Pennsylvania, New England, and New Hampshire.
Verkerk, P. J., Schelhaas, M. J., Immonen, V., Hengeveld, G., Kiljunen, J., Lindner, M., Nabuurs, G. J., Suominen, T., & Zudin, S. (2017). *Manual for the European Forest Information Scenario model (EFISCEN) Version 4.2.0*. http://www.efi.int	Carbon modelling	User manual for the European Forest Information Scenario model (EFISCEN).
Wang, T., Hamann, A., Spittlehouse, D., & Carroll, C. (2016). Locally downscaled and spatially customizable climate data for historical and future periods for North America. *PLoS ONE*, *11*(6). https://doi.org/10.1371/journal.pone.0156720	Climate change	Peer-reviewed paper introducing the ClimateNA software package, which uses long-term weather station records and climate models to make downscaled climate estimates for any point in North America from 1901 to 2100.
Wang, W., Peng, C., & Larocque, G. R. (2016). Modeling forest carbon budgets toward ecological forest management: challenges and future directions. In G. R. Larocque (Ed.), *Ecological Forest Management Handbook* (pp. 267–279).	Climate modelling	Book chapter introducing and comparing three forestry carbon accounting models (CBM-CFS, FORCARB, and CO2FIX). Includes a brief discussion of modelling challenges and future directions.
Wilson, S. A., Dipple, G. M., Power, I. M., Thom, J. M., Anderson, R. G., Raudsepp, M., Gabites, J. E., & Southam, G. (2009). Carbon dioxide fixation within mine wastes of ultramafic-hosted ore deposits: examples from the Clinton Creek and Cassiar Chrysotile deposits, Canada. *Economic Geology*, *104*, 95–112. http://pubs.geoscienceworld.org/segweb/economicgeology/article-pdf/104/1/95/3463954/95.pdf	Carbon sequestration	Peer-reviewed paper describing the natural process of carbon sequestration through the mineralization of carbonate minerals in chrysotile tailings from Clinton Creek, Yukon Territory, and Cassiar, British Columbia.

APPENDIX B — REVIEWED DOCUMENTS