A Potential Tool to Support the Prioritization of Blue Carbon Ecosystems in Canada

By

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Abstract

Globally, climate change and various anthropogenic activities have contributed to a significant decline in blue carbon ecosystems over the past few decades. These ecosystems can be prolific at accumulating and sequestering carbon dioxide and can be a vital, natural resource to mitigate increasing atmospheric carbon dioxide concentrations. Canada has the longest coastline of any country, and it has a responsibility to protect and restore these productive ecosystems. Sea-level rise is a predominant factor influencing coastal marsh's ability to remain a carbon sink in the future. Here I highlight a potential decision-making tool utilizing the Sea-level Affecting Marshes Model and Natural Capital Projects Coastal Blue Carbon model in a Canadian context. Requirements to improve the accuracy of using these models in Canada are isolated, and their integration into Canadian coastal management efforts are discussed. A high-level quantification of current and future carbon storage and sequestration in blue carbon ecosystems throughout Canada can aid future protection and restoration ambitions.

Keywords: Blue Carbon, Carbon Modelling, Coastal Ecosystems, Coastal Management, Salt Marshes, Atlantic Canada

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Chapter 1: Introduction

1.1 Context

Despite commitments by Canada and others to the Paris Climate Agreement to decrease emissions to limit warming to well below 2°C by 2100, the latest United Nations Environment Programme (UNEP) report suggests at current emission levels the world is likely to reach 2.6°C by 2100 (UNEP, 2021). Except for a temporary dip caused by COVID-19 lockdowns in 2020, emissions have been approximately increasing 1% every year for the past decade (Le Quere et al., 2020). Reportedly, most country's current emission reduction strategies are not impactful enough to prevent global warming from eventually reaching 2°C (UNFCCC, 2021). 2.4°C of warming is plausible, even with reaching the recently updated 2030 nationally determined contribution (NDCs) targets (Climate Analytics, 2021), and due to the catastrophic nature of what it presents, it has forced global mitigation strategies to research not only how to decrease present emissions, but also how to reduce the amount of carbon present in the atmosphere. The utilization of negative emission strategies is imperative moving forward to have a greater chance at preventing 2°C of warming (Moomaw et al., 2018). Nature-based climate solutions (NbCS), including the sequestration of carbon in coastal vegetation, are increasingly receiving more attention for their potential to help mitigate the impacts of the climate crisis.

NbCS is a relatively new concept that targets using nature in ways to help mitigate climate change (Nesshover et al., 2017). The European Commission expands on this notion to include the use of NbCS in addressing economic, social and environmental challenges sustainably (Krull et al., 2015, p.5). Canada sees NbCS as a critical resource in reaching its lofty commitments of protecting 25% of its land and oceans by 2025 (Government of Canada, 2020b). This paper focuses on blue carbon ecosystems, which are one aspect of NbCS whose services are figured to correspond to 20% of the value of all ecosystem services worldwide (Thorslund et al., 2017). Blue carbon, which is the carbon stored in vegetated coastal ecosystems such as seagrass meadows, salt marshes, mangroves and kelp forests, is receiving attention for its carbon storage and sequestration capacity (Filbee-Dexter & Wernberg, 2020). Carbon sequestration for blue carbon ecosystems refers to plants utilizing photosynthesis to remove CO_2 from the atmosphere and its conversion to cellulose and carbon compounds, and the process of plants decaying into soil organic matter (Moomaw et al., 2018). The ecosystems are biologically diverse, productive and provide several benefits to the surrounding environment (Santos et al., 2021).

As currently distinguished, blue carbon ecosystems have three essential components: significant greenhouse gas removal potential, an ability to store carbon for centuries and be altered to further carbon storage or negate emissions (Santos et al., 2021). Currently, salt marshes, mangroves and seagrasses are recognized as having this potential (Lovelock & Duarte, 2019), but there is reason to believe seaweeds will eventually be included (Filbee-Dexter & Wernberg, 2020). The centuries of storing carbon are attributed to their ability to hold carbon in the vegetation and underlying soil if undisturbed (Moomaw et al., 2018), and the biological hacking or micromanaging of the ecosystems could theoretically further carbon storage (Macreadie et al., 2017; Elschot et al., 2014). While blue carbon ecosystems comprise only about 0.07-0.22% of the earth's surface (Were et al., 2019), they are thought to influence a disproportionally large part of the carbon cycle (Spivak et al., 2019). It is proven that blue carbon ecosystems sequester carbon at higher rates per unit area than terrestrial ecosystems (Howard et al., 2014). For example, it is estimated that seagrasses can bury carbon 35x faster than tropical rainforests (Macreadie et al., 2014), and salt marshes sequester carbon significantly quicker too, but this rate varies depending on the marsh (Chmura, 2011). Additionally, they provide numerous co-benefits such as shoreline stabilization and protection, habitat for a diverse range of species, nutrient cycling, wave attenuation, and cultural and social value (Vierros et al., 2019).

The three main types of blue carbon ecosystems found in Canada are salt marshes, seagrasses and seaweed ecosystems. Salt marshes, which will be the focus of this paper, are most commonly found in temperate or subtropical coastal lagoons, embayment areas and estuaries (Macreadie et al., 2019) within the intertidal zone. Meanwhile, varying types of seagrasses can be found globally in environments within both the intertidal and subtidal zones (Unsworth et al., 2019). Over the past 50-100 years, there has been a global decline of 25-50% of salt marshes and seagrasses (Pendleton et al., 2012; Vierros et al., 2019). For the Canadian context, the Bay of Fundy has lost approximately 85% of its salt marsh habitat since the 17th century (Virgin et al., 2020), and the lower mainland has seen 70% of tidal wetlands disappear (Simmons et al., 1978). To utilize these ecosystems as a participant in its carbon emission mitigation strategy, Canada must do a better job at protecting and restoring them.

1.2 Management Problem

Over the past few decades, approximately one-third of the total coastal blue carbon ecosystems have been lost globally (Wylie et al., 2016). It could be argued that Canada bears more responsibility than most as it has the most extensive coastline of any country in the world, therefore having an above-average need to protect and restore these highly productive ecosystems. Salt marshes are susceptible to destabilization from varying anthropogenic and climate change-related effects, resulting in the emission of previously stored carbon when these sites are degraded or destroyed (Vierros et al., 2019; Pendleton et al., 2012*)*. In the past, coastal decisions were not made with blue carbon ecosystem's wellbeing in mind (Wollenberg, Ollerhead & Chmura, 2018) and have been overlooked during policy creation (Brown et al., 2021). The lack of consensus among the scientific community, industry and communities of how to value these known ecosystem services, especially quantitatively, has hindered the promotion of their protection and restoration. Blue carbon ecosystems are becoming more recognized for their value to potentially contribute to national carbon budgets (Sutton-Grier & Moore, 2016), but Canada's quality of carbon storage and geospatial data currently limits their involvement (Postlethwaite et al., 2018).

Coastal wetlands are “special types of wetlands that are influenced by water levels to provide a habitat for a vast array of organisms, including many endangered species” (Sivaperuman & Venkatraman, 2015). However, until recently, they failed to receive recognition for the ecosystem services they provide and their benefits in mitigating climate change (Unsworth et al., 2019). In some regions, these wetlands preceded what are now homes to aquaculture, housing developments, agriculture and other industrialization efforts (Kirwan & Megonigal, 2013). Trends over the past centuries have seen increased development in the coastal zone and some cases, the formation of megacities (Pelling & Blackburn, 2013). As human concentration in these areas expands, it could present an increased level of risk due to the uncertainty that climate change, and with it sea-level rise, more frequent and powerful storms and flooding, present (Pelling & Blackburn, 2013). Difficult decisions about the need to begin retreating from coastlines have begun in certain areas where the risk outweighs the reward to continue to inhabit the area (Dannenberg et al., 2019). This solution is not practical for densely populated areas, nor is it a popular idea. However, in places where relocation is possible, there could be potential to restore that coastal area to how it once was.

In addition to anthropogenic threats, blue carbon ecosystems, particularly salt marshes in Canada, are vulnerable to inundation from sea-level rise (Gonneea et al., 2019). When coastal wetlands have either vertical or lateral landward accommodation space, the overall carbon storage capacity of the wetland can increase with response to relative sea-level rise (Rogers et al., 2019). As the sea level rises, more organic minerals will accumulate, creating more potential burial space for carbon (Rogers et al., 2019). However, if steep slopes and minimal accommodation space constrain the wetland, there is no opportunity for adaptation with sea-level rise, and "coastal squeeze" can occur (Chmura, 2011). A tipping point exists where relative sea-level rise occurs faster than the marsh can transgress landward, which can result in the vegetation drowning (Crosby et al., 2016). This is demonstrated as biomass slowly dies off, and the previously covered vegetated land becomes a tidal flat. The conversion facilitates more significant oxidization of previously stored carbon which is then expelled to the atmosphere as carbon dioxide (Pendleton et al., 2012). This critical juncture is widely unclear for most salt marshes as various ecogeomorphic factors, and different equilibrium and threshold points create a difficult equation to predict future viability (Kirwan et al., 2016).

The mapping of blue carbon ecosystems in Canada is incomplete, coupled with the dynamics of sea-level rise varying in different coastal environments causes underlying uncertainty when planning future mitigation efforts (Postlethwaite et al., 2018; Chisholm et al., 2021). Additionally, unforeseen disturbances to salt marshes can threaten the release of previously sequestered carbon. These factors create a quandary when attempting to quantify the potential contribution that blue carbon ecosystems can have on Canada's future national carbon emissions policy. It is necessary to analyze these coastal ecosystems and investigate their potential for accommodation, survival, and carbon sequestration capacity (Beeston, Cuyvers & Vermilye, 2020).

1.3 The Research Objective

This paper will seek to outline tools being used in other parts of the world that could assist in prioritizing blue carbon ecosystems for protection or restoration in the future for Canada. Most blue carbon research is conducted by field studies and sampling areas of interest.

This data and knowledge can be applied to various modelling software such as the Sea-level Affecting Marshes Model (SLAMM) and InVEST's Coastal Blue Carbon (CBC) tool. Sometimes, it is not feasible to sample every ecosystem because of the time and money it requires. While salt marshes are quite heterogeneous, in certain situations where time and money are of the essence, it could be possible that proxy's for carbon storage such as climate, soil type, sedimentary classification and land management strategies (Ford et al., 2019) can inform modelling scenarios. This research aims to highlight these modelling tools and their potential transferability to create high-level estimates of carbon storage and sequestration in Canada. Thus, demonstrating the potential to create a valuable resource for coastal managers throughout Canada. Modelling tools are highlighted by analyzing a couple of case study areas, and through investigating these tools, some central themes will be explored:

1. The uncertainty of future sea-level rise, possibly leading to the inundation of salt marshes, threatening their ability to act as a carbon sink.
2. What changes can be made to improve the effectiveness of these modelling techniques in Canada to give a high-level valuation of potential carbon storage in a specific wetland?
3. How does this tool fit into Canada's overall coastal management goals?
4. How can these tools assist in the protection and restoration of blue carbon ecosystems?

1.4 Blue Carbon Process

Blue carbon ecosystems utilize photosynthesis to store and sequester carbon by accumulating it in their biomass and through the slow decomposition of carbon that rests in their underlying sediment (Lovelock & Reef, 2020) (Figure 1)

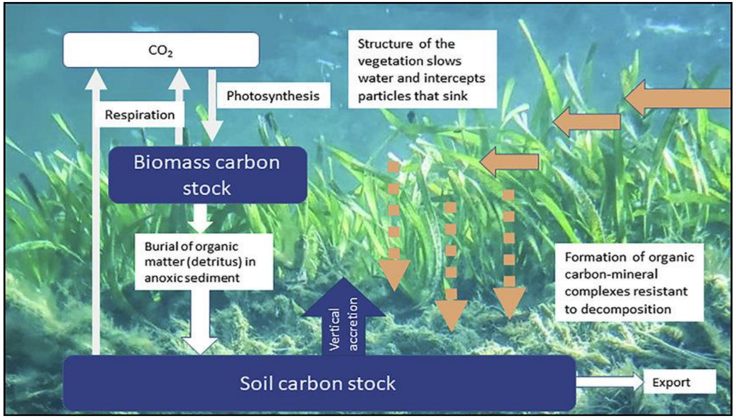


Figure 1 How blue carbon accumulates in coastal ecosystems. This picture illustrates the most common ways carbon accumulates: photosynthesis of CO_2 *and vegetation trapping sediment (Lovelock & Reef, 2020).*

The rate at which carbon is sequestered varies and depends on the type of ecosystem in question (i.e. salt marsh, seagrass, etc.) and environmental factors such as latitude, tidal range, temperature, elevation and microbial interactions (Ouyang & Lee, 2014). The range of variables within a given ecosystem creates uncertainty within the modelling process. Further, predicting complex concepts like hydrodynamics and sediment dynamics is challenging as ecosystem forces create a greater range of outcomes (Fitzgerald & Hughes, 2019). This complexity can be exemplified by examining temperature as a variable. Increases in temperature cause more primary productivity, leading to higher carbon dioxide removal rates from the atmosphere. However, it also causes increased microbial activity in the soil, which speeds up decomposition, leading to higher rates of carbon being emitted back to the atmosphere as carbon dioxide (Wang et al., 2019).

The ability of salt marshes located in the intertidal zone to migrate either vertically or horizontally as sea-level rises are the dominating factor that contributes to their longevity (Li et al., 2018). The vertical transition is facilitated by organic and inorganic sediment deposition, surface erosion and the relative-sea-level rise, while horizontal progression is driven by lateral erosion processes (Marani et al., 2011). If the salt marsh's ability to trap inorganic sediments and accumulate organic matter lessens, particularly in low-lying areas, a negative feedback loop can appear, and inundation is possible because there will be continually less time for photosynthesis to occur (Kirwan & Megonigal, 2013). This process is influenced by several other factors, including local subsidence, sedimentation and subsurface expansion (Kirwan & Megonigal, 2013). The full extent of this process takes decades and is subject to several factors, including elevation, species composition and landward adaptation space (Crosby et al., 2016), which provides ample time for active management strategies to mitigate or avoid the loss.

Overall, the blue carbon ecosystem's carbon burial rate is greater per unit area than terrestrial ecosystems (Mcleod et al., 2011). This is primarily due to their productivity and ability to preserve carbon in the underlying sediment (Rogers et al., 2019). Additionally, unlike terrestrial ecosystems, marine ecosystems continue to accumulate soil over time. Accretion provides more significant carbon burial since it coincides with the extent of the anoxic environment increasing (Connor et al., 2011). Anoxic environments promote slower decomposition rates of carbon by microbes, fostering more long-term carbon sequestration.

1.5 Managing Blue Carbon Ecosystems

To correctly manage and account for blue carbon ecosystems, factoring in their future response to climate change is essential (Santos et al., 2020). Formalizing a one-size-fits-all response to how blue carbon ecosystems should be managed in the future is impossible due to differences within each physical environment and its jurisdictional boundaries (Li et al., 2018). Also, adding to the situation's complexity is that the extent of mapping these ecosystems has yet to be completed in Canada (Postlethwaite et al., 2018), and what has been done is yet to be centralized (Ouyang & Lee, 2014). Historically, prioritizing the betterment of blue carbon ecosystem health, which would lead to greater mapping and management advances have been absent in international policy agendas (Brown et al., 2021). However, as these ecosystems have become more widely recognized for the benefits they provide, now a greater emphasis needs to be placed on data collection and use of remote technologies for monitoring. Some fiscal support is provided by the government, private interests and non-profits for the conservation of coastal salt marshes. However, sometimes the reality is that in the long-term, sustainability might not be possible (Chmura, 2013). Saltmarsh sustainability has been a focus of conversation over the past two decades (FitzGerald and Hughes, 2019). Global predictions of whether salt marshes will succumb to sea-level rise by the end of the century are uncertain. Various studies have reported that 60-91% of salt marshes are not keeping pace with sea-level rise worldwide (Crosby et al., 2016), yet less than 5% of areas considered “low marsh” in North America and Europe are currently submerging (Kirwan et al., 2016). This contrast further demonstrates how every salt marsh should be managed individually, exacerbating time and resource requirements.

A consensus has yet to be reached regarding how to value blue carbon ecosystems or other ecosystem services (Macreadie et al., 2019). The array of services they provide and innate variability within them, combined with a degree of subjectiveness to some of their other benefits (cultural and recreational value), produce a complicated equation. Coastal protection (ability to mitigate coastal erosion and damage to infrastructure) and carbon storage are the two main services that research has used to quantify, thus simplifying that equation (Seddon et al., 2020; Wollenberg, Ollerhead & Chmura, 2018). If a coastal wetland's carbon stock is approximately known, the total amount of carbon sequestered over time can be modelled by factoring in the extent of the wetland and the accumulation rate (Wedding et al., 2021). By modelling how this process might evolve, the results can be a piece of the puzzle in future coastal management plans.

The protection and restoration of blue carbon ecosystems can help meet Sustainable Development Goals (SDG) 13.2 (integrate climate change measures into national policies, strategies and planning) & 14.2 (using ecosystem-based approaches to managing marine areas), in addition to contributing to protected area targets committed to as a signatory to the Convention on Biological Diversity (Wedding et al., 2021). It is possible to remediate formerly destabilized blue carbon ecosystems to become net carbon sinks again (Greiner et al., 2013). Further, restoring coastal areas that have been dyked back to marsh has been shown to offer more significant carbon sequestration benefits than repairing terrestrial ecosystems (Connor, Chmura & Beecher, 2001). However, it is uncertain what management practices have the most significant impacts on carbon sequestration of coastal wetlands (Howard et al., 2014), and the exact relationship between carbon sequestration in natural versus restored ecosystems has yet to be fully quantified (Byun, Lee & Kang, 2019). Current unpredictability comes from variables, including physical characteristics, topography, historical land uses, and previous restoration activities (Yu et al., 2017). Further, there is a wide range of carbon storage rates and densities in wetlands (Were, 2019) as this often ranges by several hundred megagrams of carbon per hectare depending on the study location (Howard et al., 2014). The broad range and uncertainty on the carbon sequestration-emission axis present another obstacle in creating a formal blue carbon ecosystem valuation protocol.

Chapter 2: Methodology

2.1 Study Design

The design of this project is a summation of several prominent themes discovered during a blue carbon literature review. One is the necessity to create a high-level valuation of coastal ecosystems that can be quantified (Beeston, Cuyvers & Vermilye, 2020). Numerically quantifying ecosystem services is a complex endeavor, especially when trying to combine the various services. For this report, the quantification of blue carbon in Canadian ecosystems was the focus. Second, the practical reality of anthropogenic effects combined with accelerating relative sea-level rise causing future inundation of salt marshes must be considered (Delaune &

White, 2012). This valuation needs to consider potential inundation due to sea-level rise since any carbon storage benefit is forfeited under this condition. Using these as central points to craft the study, it pointed to the best-fit use of both the Sea-level Affecting Marshes Model (SLAMM) and Natural Capital's Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)
Two Canadian case study areas were selected and analyzed using ArcGIS Pro™, SLAMM and InVEST's Coastal Blue Carbon (CBC) tool[1] to model future carbon sequestration and emissions of salt marshes under the influence of sea-level rise[2]. ArcGIS Pro was used to delineate the area of interest and create raster files that SLAMM could interpret. SLAMM builds land use and land cover maps of the desired year based on several inputs. Finally, the CBC tool interprets the land cover maps to articulate the amount of carbon sequestered during different time periods. The study also aims to identify current data limitations and make recommendations on how these tools could be used in future coastal management decision-making in Canada.

2.2 Tools Used

****** For more information see the Appendix***

1. ArcGIS Pro

For each case study area, LiDAR data acquired from their respective provincial government websites was used to facilitate the creation of a high-quality Digital Elevation Model (DEM). Subsequently, using this model to create a slope profile of the area applying geoprocessing tools. For land cover information, specific wetland classes were delineated and adjusted to fit the requirements of the SLAMM model while formatted as a shapefile. Once the three layers were formatted to the same extent and matching cell size, columns and rows, they were converted to ASC ll files for compatibility with SLAMM.

2. Sea-Level Affecting Marshes Model (SLAMM)

SLAMM is a tool that coastal managers can use to identify risks and opportunities to restore coastal wetlands (Glick et al., 2013). The SLAMM model has been in use since the mid-1980s to simulate the main processes involved in coastline and wetland conversion when experiencing sea-level rise (Clough & Larson, 2010). It has been used extensively by the U.S. Fish and Wildlife Service (Kirwan et al., 2016) and planning agencies like the New York State Energy Research and Development Authority (Clough, Polacyzk & Propato, 2016). However, its uptake in Canada has thus far been limited. SLAMM processes three raster layers created on ArcGIS Pro and offers the ability to integrate several other variables to fine-tune the model. It can provide information on how elevation, habitat type, slope, accretion, and erosion are affected by seawater inundation and the conversion of the wetland habitat types (Glick et al., 2013), making SLAMM an effective tool to gauge probabilities of how sea-level rise will affect marshes (Clough, Polacyzk & Propato, 2016).

3. Coastal Blue Carbon (CBC) tool

Natural Capital Project's InVEST suite encompasses a broad range of modelling tools supporting decision-making strategies (InVEST, 2021). These tools have been used by governments, non-profits and corporations to balance the potential trade-off between economic and environmental goals (InVEST, 2021). For this project, the CBC tool was used to find the amount of carbon sequestration and carbon emitted that occurs in a salt marsh, over a designated period of time. The tool has two parts: first is a preprocessor that creates a land cover matrix over time, and second is a blue carbon calculator (Richmond et al., 2015). It uses land cover type as a proxy for carbon storage in the corresponding area, and as this area changes over time based on the land-use maps created in SLAMM, the quantity of carbon stored can change. The amount of carbon that a particular land cover type stores is designated by the user, along with the percentage of carbon lost depending on the type of disturbance it endures (high, medium or low impact).

2.3 Investigation

2.3.1 Study Areas

There were a few determining factors when choosing the Canadian salt marsh locations that were going to be used to guide the report. First, the area must have high-quality LiDAR (Light Detection and Ranging) data and some form of wetland delineation data due to SLAMM requirements. Second, the areas chosen would be geomorphologically contrasting to see how marshlands with different surroundings would react to future sea-level rise in the model. Third, in a recent estimate for carbon emission mitigation from salt marsh restoration, Atlantic Canada, specifically Nova Scotia and New Brunswick, had the highest potential in Canada (Drever et al., 2021). Thus, leading to Southwest Nova Scotia and St. Martins, New Brunswick as the chosen locations.

Pinkney's Point, located in Southwest Nova Scotia, is on a peninsula about 20km southeast of Yarmouth, surrounded by the Tusket Islands. It is located on the eastern seaboard of Canada, which along with the rest of the southern part of Nova Scotia, is experiencing one of the fastest accelerations in relative sea-level rise in Canada (Han et al., 2016). St. Martins, New Brunswick, is located about 50km east of Saint John on the upper-middle New Brunswick side of the Bay of Fundy. Its tidal marsh area is exposed to some of the highest tides in the world, as the tidal range in St. Martins can reach 38 feet (SMDCC, 2021). Also, it is surrounded by elevated cliffs that run in a semi-circular manner which encompasses the marsh. Its substantial tidal range, combined with steep elevation, makes it a perfect contrast to the low-lying Tusket islands landscape.

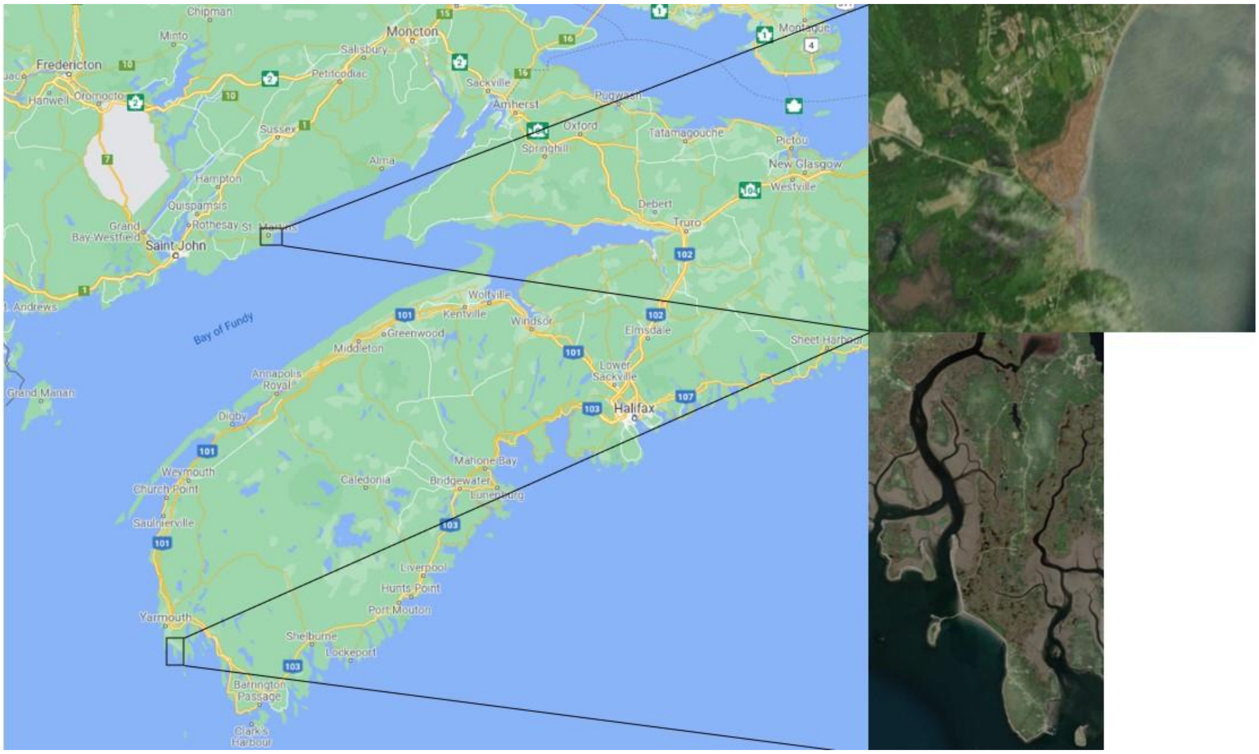


Figure 2 Locations of the case study areas in St. Martins, New Brunswick and near Pinkney's Point Nova Scotia (Google, n.d.)

2.3.2. Case Study Methodology: Southwest Nova Scotia

****** For the complete walkthrough, see Appendix A***

The first step is to create the input rasters for SLAMM (Table 1). SLAMM requires a DEM raster, wetland raster and slope raster. LiDAR data is acquired from the Nova Scotia government website to create the DEM (Figure 3) and slope files (Figure 4). Due to Canada's lack of a national wetland inventory, the Ecological Land classification Data (ELC) on the Open Data Nova Scotia website is used. SLAMM requires the wetland inventory set to a specific land type cover (ex. undeveloped dry land, coastal beach, regularly flooded marsh), which the ELC data did not match. This conversion required significant manual delineation by superimposing the wetland data over the LiDAR data and double-checking accuracy with Google Earth. Future work could include utilizing deep learning strategies to enhance the accuracy of delineating different land classes.

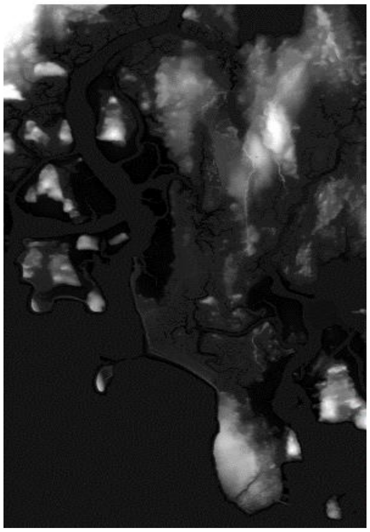


Figure 3 Digital Elevation Model (DEM) of Pinkney's Point, Nova Scotia. Generated by LiDAR from https://nsgi.novascotia.ca/datalocator/elevation/

Table 1 Steps to create SLAMM inputs. An outline of the steps that were taken to produce the necessary raster files.

ArcGIS Pro Process
1. Acquire LiDAR and wetland data
2. Create a Digital Elevation Model (DEM) from LiDAR data
3. Align vertical datum of DEM to Mean Sea Level (MSL)
4. Create slope raster file from DEM raster
5. Adjust wetland data categories to SLAMM category requirements
6. Ensure wetland data and DEM are aligned, manually fix if necessary
7. Create wetland raster file from wetland shapefile
8. Convert raster files to SLAMM required ASC ll

Figure 4 Slope raster of Pinkney's point, Nova Scotia created from DEM

Also, the files had a slight offset throughout different parts of the region (Figure 5) that had to be corrected before being input into SLAMM. Changes were made to match the ELC land cover types to the SLAMM requirements. The lack of delineation in the ELC Nova Scotia data between high and low marsh limits the model's ability to define the difference between "regularly flooded" and "transitional" marsh. In this report, ELC defined areas called "Saltmarsh," are changed to "regularly flooded marsh."

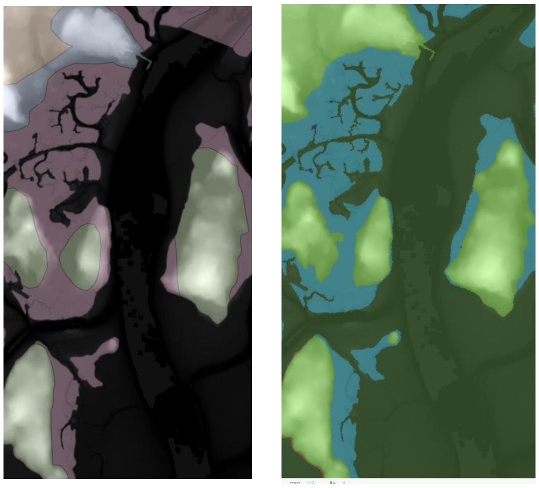


Figure 5 An example of the spatial offsets seen between the DEM and wetland data that had to be corrected

SLAMM data inputs are required to be in respect to the same geodetic datum. A geodetic datum is "an abstract coordinate system with a reference surface (such as sea level) that serves to provide known locations to begin surveys and create maps" (NOAA, 2021). While the horizontal datums used in data inputs aligned, the vertical datums did not. SLAMM expects its elevation data inputs (i.e. DEM, Slope files) to be formatted concerning Mean Sea Level (MSL) as the vertical datum. Nova Scotia government's LiDAR data's vertical datum is represented in CGVD 2013, a geoid-based datum. This meant that the LiDAR data had to be converted before it could be inputted into SLAMM. Canada's vertical datum before CGVD2013 was CGVD28, a tidal datum with its reference point as MSL (GeoNova, 2016). In Nova Scotia, CGVD2013 is approximately 60 cm above CGVD28 (GeoNova, 2016); this approximation was the theory used behind the manual transformation. The science of converting the LiDAR data manually to MSL is not perfect (See Appendix A). However, the calculated adjustment works within the realms of this study, focusing on how these tools can be applied to Canada's coastal management objectives.

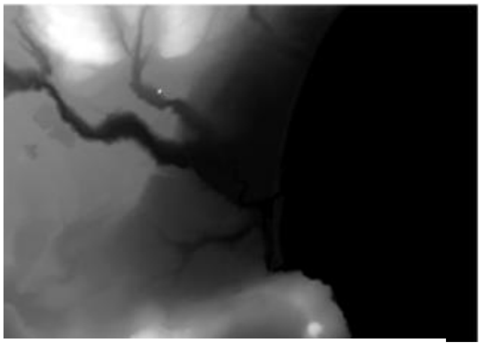


Figure 6 Digital Elevation Model (DEM) of St. Martins, NB. Generated by LiDAR from https://geonb.snb.ca/li/

2.3.3. Case Study Methodology: St. Martins, New Brunswick

* For the complete walkthrough, see Appendix B**

Creating a DEM and slope file for this case study was accomplished by acquiring the LiDAR data from the GeoNB website (Figure 6; Figure 7). For New Brunswick’s LiDAR data, there was an option to select the vertical datum in reference to CGVD2013 or CGVD28, making the manual transformation of aligning the vertical datum to MSL easier. The wetland raster was created by combining recent wetland data and ELC data shapefiles from GeoNB. Some manual delineation of land cover was necessary before conversion to a raster file. New Brunswick's latest wetland data does a better job at delineating different wetland types than NS ELC data. Similar to the Nova Scotia data, land cover types are not directly related to the SLAMM categories and were converted.

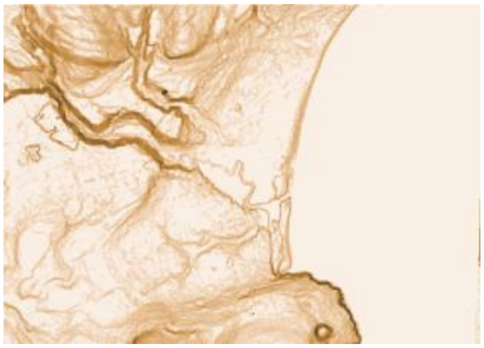
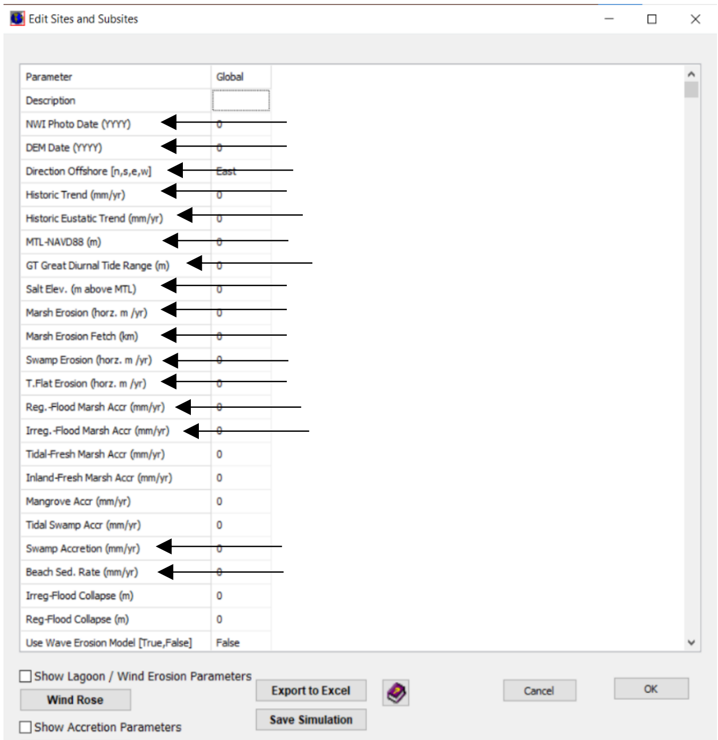


Figure 7 Slope raster of St. Martins, NB

2.3.4 *SLAMM and InVEST*

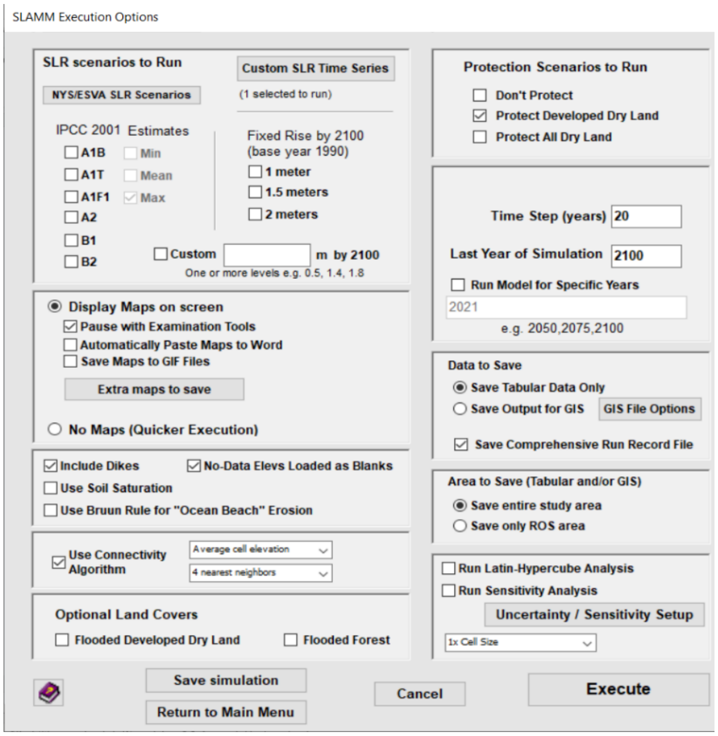
The model's parameters can be defined once the three raster files are built and inputted into SLAMM. The parameters consist of variables such as erosion and accretion rates per year, tidal range, meters above salt elevation and historical rates of sea-level rise (Figure 8). The execution phase of SLAMM follows, where scenarios can be run based on different levels of future sea-level rise and those running the tool can choose whether to protect dry land or allow possible marsh migration (Figure 9). It shows how different amounts of sea-level rise will affect marshes, whether they succumb to inundation, and, if so, in how many years. Once the scenarios are finished running and completed, land cover rasters are created that can be integrated into the CBC tool. Inputting the different scenarios of land cover rasters into the CBC tool shows the amount of carbon sequestered or emitted during designated time periods. The process is customized by designating the amount of carbon



Parameter	Global
Description	
NWI Photo Date (YYYY)	0
DEM Date (YYYY)	0
Direction Offshore [n,s,e,w]	East
Historic Trend (mm/yr)	0
Historic Eustatic Trend (mm/yr)	0
MTL-NAVD88 (m)	0
GT Great Diurnal Tide Range (m)	0
Salt Elev. (m above MTL)	0
Marsh Erosion (horz. m /yr)	0
Marsh Erosion Fetch (km)	0
Swamp Erosion (horz. m /yr)	0
T.Flat Erosion (horz. m /yr)	0
Reg.-Flood Marsh Accr (mm/yr)	0
Irreg.-Flood Marsh Accr (mm/yr)	0
Tidal-Fresh Marsh Accr (mm/yr)	0
Inland-Fresh Marsh Accr (mm/yr)	0
Mangrove Accr (mm/yr)	0
Tidal Swamp Accr (mm/yr)	0
Swamp Accretion (mm/yr)	0
Beach Sed. Rate (mm/yr)	0
Irreg-Flood Collapse (m)	0
Reg-Flood Collapse (m)	0
Use Wave Erosion Model [True,False]	False

Figure 8 Defining SLAMM parameters and variables box. The values and justifications for Pinkney’s Point and St. Martins can be found in Appendix C and D respectively. Arrows emphasize the parameters applied in this study.

in the biomass, soil and litter. These values can be found through relevant field studies in the area or *possibly* the use of proxies. This number acts as the starting figure, and as the model progresses through time, it can go through land cover changes (i.e. marsh to transitional marsh to tidal flat). How substantial of an impact a land-use type change will have on the carbon storage can be designated beforehand by low, medium or high impact.


SLAMM Execution Options

SLR scenarios to Run
(1 selected to run)
IPCC 2001 Estimates
☐ A1B ☐ Min
☐ A1T ☐ Mean
☐ A1F1 ☑ Max
☐ A2
☐ B1
☐ B2
Fixed Rise by 2100 (base year 1990)
☐ 1 meter
☐ 1.5 meters
☐ 2 meters
☐ Custom m by 2100
One or more levels e.g. 0.5, 1.4, 1.8

● Display Maps on screen
☑ Pause with Examination Tools
☐ Automatically Paste Maps to Word
☐ Save Maps to GIF Files
○ No Maps (Quicker Execution)

☑ Include Dikes
☑ No-Data Elevs Loaded as Blanks
☐ Use Soil Saturation
☐ Use Bruun Rule for "Ocean Beach" Erosion

☑ Use Connectivity Algorithm: Average cell elevation; 4 nearest neighbors

Optional Land Covers
☐ Flooded Developed Dry Land
☐ Flooded Forest

Protection Scenarios to Run
☐ Don't Protect
☑ Protect Developed Dry Land
☐ Protect All Dry Land

Time Step (years) 20
Last Year of Simulation 2100
☐ Run Model for Specific Years
2021
e.g. 2050,2075,2100

Data to Save
● Save Tabular Data Only
○ Save Output for GIS
☑ Save Comprehensive Run Record File

Area to Save (Tabular and/or GIS)
● Save entire study area
○ Save only ROS area

☐ Run Latin-Hypercube Analysis
☐ Run Sensitivity Analysis
1x Cell Size

Figure 9 Execution options for SLAMM. During the analysis. Eight different scenarios were run considering different future sea-level rise scenarios and protection protocols.

Chapter 3. Modelling Debrief

3.1 Findings and Limitations

LiDAR Data

There were several notable findings when attempting to use the SLAMM and CBC tools on Canadian blue carbon ecosystem case studies. Some data requirements were publicly available and easy to find, whereas others were limited at best. The High-Resolution Digital Elevation Model recently released by the Government of Canada combined with LiDAR data provided by provinces made that prerequisite for SLAMM relatively easy to attain. The software itself limited the quality of data provided by Canada as cell size had to be increased (5x5 meters) for SLAMM to run as it does not perform well with fine resolutions (Glick et al., 2013).

An aspect that needs to be resolved is the synchronization of vertical datums between data acquisition and modelling software used. In simple terms, the United States and Canada used to use a similar tidal datum as their primary vertical datum for elevation data, but due to their limitations, the United States adapted NAVD88; meanwhile, Canada's changed its standard to CGVD2013. This has caused a discrepancy between different types of modelling software and the reference point used when acquiring data. The United States also has VDatum, a user-friendly software that assists in changing data from one datum to another (https://vdatum.noaa.gov/about.html), and some vertical data conversions are possible within

ArcGIS Pro. However, there are limited user-friendly options for converting Canadian datums and transformations within ArcGIS Pro are limited.

Wetland Data

The difference between wetland data availability in the United States and Canada emerged as a theme throughout looking for quality data for this report. The U.S. Fish and Wildlife Service has created a national wetland inventory, while Canada's finer scale wetland data is decentralized, inconsistent across jurisdictions and limited in some cases. In the context of this study, New Brunswick has improved, recently released GeoNB wetland data, whereas Nova Scotia does not have a wetland delineations specific dataset publically available. For this project, ELC data was used for Nova Scotia because it was the best publicly available resource to use as a starting point. There was a significant amount of time spent using manual delineation to fix offsets between the wetland and lidar data and land cover classes. Due to these offsets, upon synchronization of the rasters into SLAMM, it was not possible to align the data sets at time "zero" without changes taking place. This alignment issue creates a subtle difference in what the actual conditions of the area are and what is inputted into the model, creating uncertainty. Further, the detail and accuracy of LiDAR data picks up subtleties that the wetland data does not because it is acquired at a higher resolution than at which the wetland data is created.

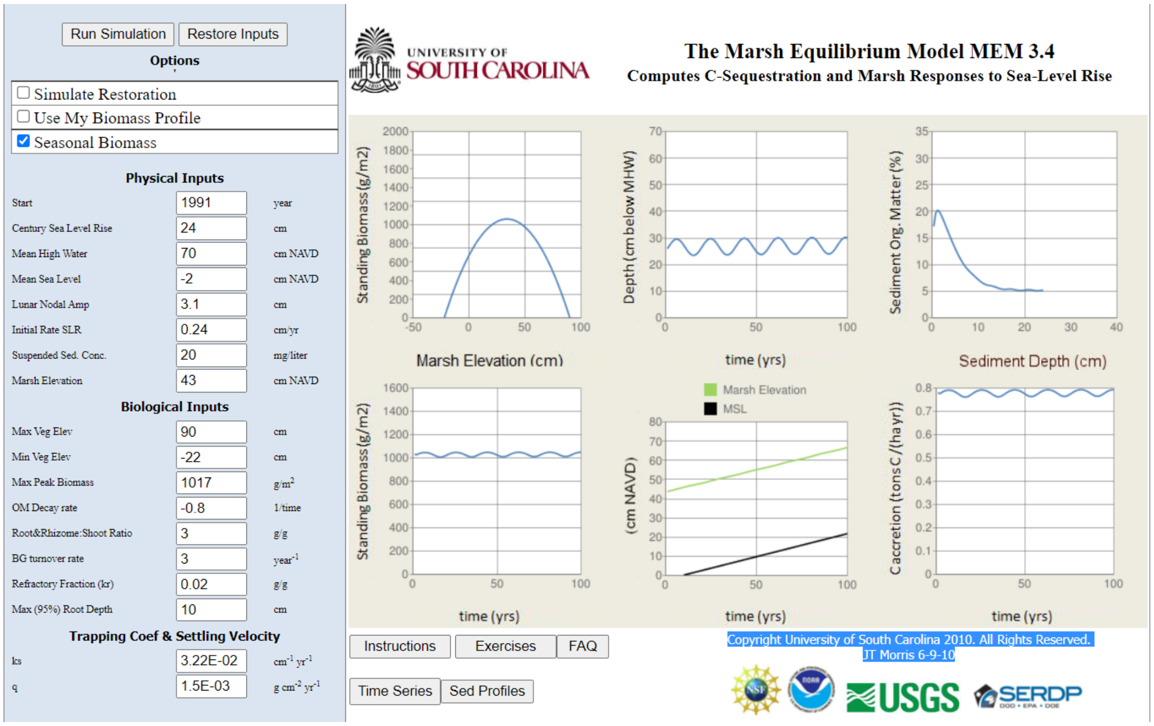
Generating wetland data is a static process where different land cover types are defined at exact locations. This presents issues when attempting to delineate dynamic intertidal zones where the coastal environment is covered differently depending on the time of day. Using remote sensing to define environments and ecosystems that are hidden by the tides periodically is a current limitation globally (Murray et al., 2018), and there is an overall lack of studies on where salt marshes should be located with respect to tidal ranges and tidal datums (Balke et al., 2016). As discussed in the 2019 IPCC report on Oceans and Cryosphere, sufficient responses to climate change include coordination between governing bodies to enable data sharing to increase the capacity of resilience planning (Pörtner et al., 2019). Without a defined initiative across governing bodies in Canada to increase data solutions, the utilization of tools that can assist in blue carbon tracking will be unlikely.

SLAMM and InVEST Inputs

While conducting some field studies will be necessary to collect numerical data on carbon accumulation, erosion and accretion rates and depending on the study, it may be possible to use this information again and guide management of other similar ecosystems of interest. However, the heterogeneity within and between blue carbon ecosystems regarding carbon storage (Gallant et al., 2020) should be noted as a potential limiting factor. If creating a high-level estimate is the goal, this should not be a major deterrent. Although models are only as effective as the defined parameters, it was notable that there is a lack of recent accretion and erosion rate data available. An additional limiting aspect is how the CBC tool splits carbon storage into biomass, soil and litter, and accumulation rates for each. Rarely in Canadian blue carbon literature is carbon storage defined that specifically. The incongruity between these two factors shows of an example situation where greater collaboration and planning across disciplines is necessary for effective ecosystem management.

Limitations

As with all models, certain limitations are present. The SLAMM model was initially developed to map ecosystem change but is often used to track coastal landscape changes (Nuse, Cooper & Hunter, 2015). This is despite SLAMM's base model not accounting for physical processes within the ecosystems other than by using a fixed rate (FitzGerald & Hughes, 2019). Since ecosystem dynamics will evolve over decades, more recent studies have integrated other modelling techniques into SLAMM for a more accurate view of coastal evolution (Kirwan et al., 2016). It has been suggested to use the Marshes Equilibrium Model (MEM) (Figure 10) to create a more mechanistic model for accretion dynamics to input into SLAMM as opposed to using empirical curves (Gonneea et al., 2019; FitzGerald & Hughes, 2019). This would have been explored in this report if it had been compatible with Canadian vertical datums; however, it requires inputs in NAVD88. SLAMM not being a hydrodynamic model limits its ability when accounting for land cover transitions such as a tidal flat or coastal beach adjacent to open water. It does not interpret any erosion or aggradation (deposition of sediment) contributed by non-tidal sources (Clough, Polacyzk & Propato, 2016).



Options

☐ Simulate Restoration
☐ Use My Biomass Profile
☑ Seasonal Biomass

Physical Inputs

Start	1991	year
Century Sea Level Rise	24	cm
Mean High Water	70	cm NAVD
Mean Sea Level	-2	cm NAVD
Lunar Nodal Amp	3.1	cm
Initial Rate SLR	0.24	cm/yr
Suspended Sed. Conc.	20	mg/liter
Marsh Elevation	43	cm NAVD

Biological Inputs

Max Veg Elev	90	cm
Min Veg Elev	-22	cm
Max Peak Biomass	1017	g/m^2
OM Decay rate	-0.8	1/time
Root&Rhizome:Shoot Ratio	3	g/g
BG turnover rate	3	$year^{-1}$
Refractory Fraction (kr)	0.02	g/g
Max (95%) Root Depth	10	cm

Trapping Coef & Settling Velocity

ks	3.22E-02	$cm^{-1}\ yr^{-1}$
q	1.5E-03	$g\ cm^{-2}\ yr^{-1}$

Figure 10 Marsh Equilibrium Model (MEM)™ interface. (Morris, 2010).

Chapter 4: Results

Overall, by running these two case studies through SLAMM and the CBC tool, albeit with several limitations and caveats, neither salt marsh completely succumbed to sea-level rise by 2100. In no circumstance should these results be interpreted verbatim because there are obvious limitations to the current methods and were run with mostly proxy information or default settings (see Appendix C and Appendix D for more information on biophysical inputs used within the model). At the end of the study, eight different trial runs were tested (Figure 11), although, in the future, the hope would be to run significantly more trials per case study under varying circumstances.

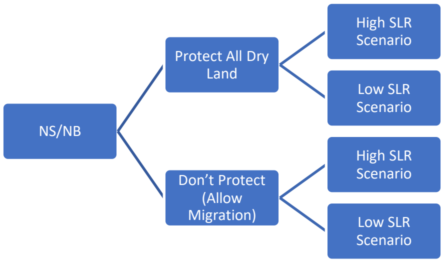


Figure 11 The different scenarios that were run during the modelling process for Pinkney's Point and St. Martins

While only certain conditions were run, and the overall results pertain to going through the process of using these tools in Canada, and what can be improved so that they can be used for future coastal decision-making, high-level trends were observed. In St. Martins (Figure 12), the greater part of the marsh was able to keep pace with sea-level rise throughout the entire model, ending in 2100.

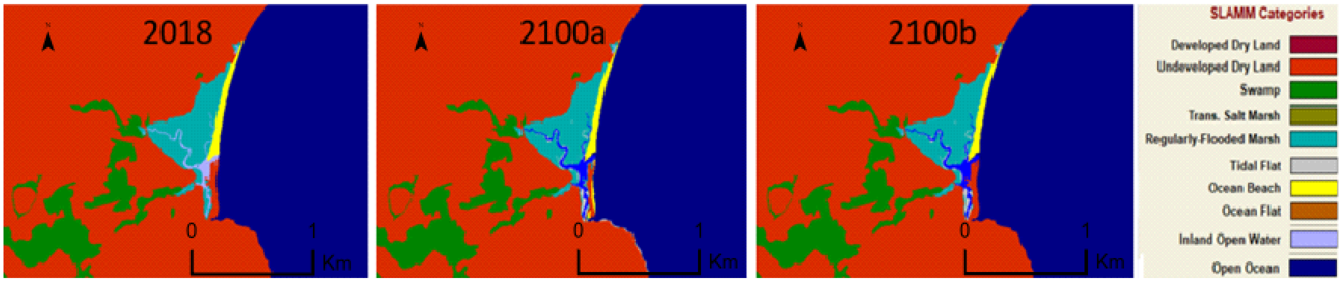


Figure 12 St. Martins SLAMM model from time zero in 2018 to 2100. Both 2100 models are run under the high sea-level rise scenario (1.33m). 2100a is using unprotected dry-land and 2100b is a protected dry-land scenario.

There was a lack of transitional marsh (marsh migrating landward), which could have significance post-2100 as the area behind the marsh is elevated significantly higher, making it difficult for marsh adaption to sea-level rise. This also could be due to the lack of differentiation between irregularly and regularly flooded marsh or the methodology behind synchronizing the vertical datums. For Pinkney's point model, the major noticeable factor was the difference between 2080 and 2100 and the conversion of regularly flooded marsh to tidal flat (Figure 13). The low-lying nature of the area, and high rates of sea-level rise in Southwest Nova Scotia, present a chance of future inundation. However, due to the region's complexities (i.e. Barrier islands) and oversimplification of the model, especially in this case without accurate inputs for accretion dynamics, this requires further examination.

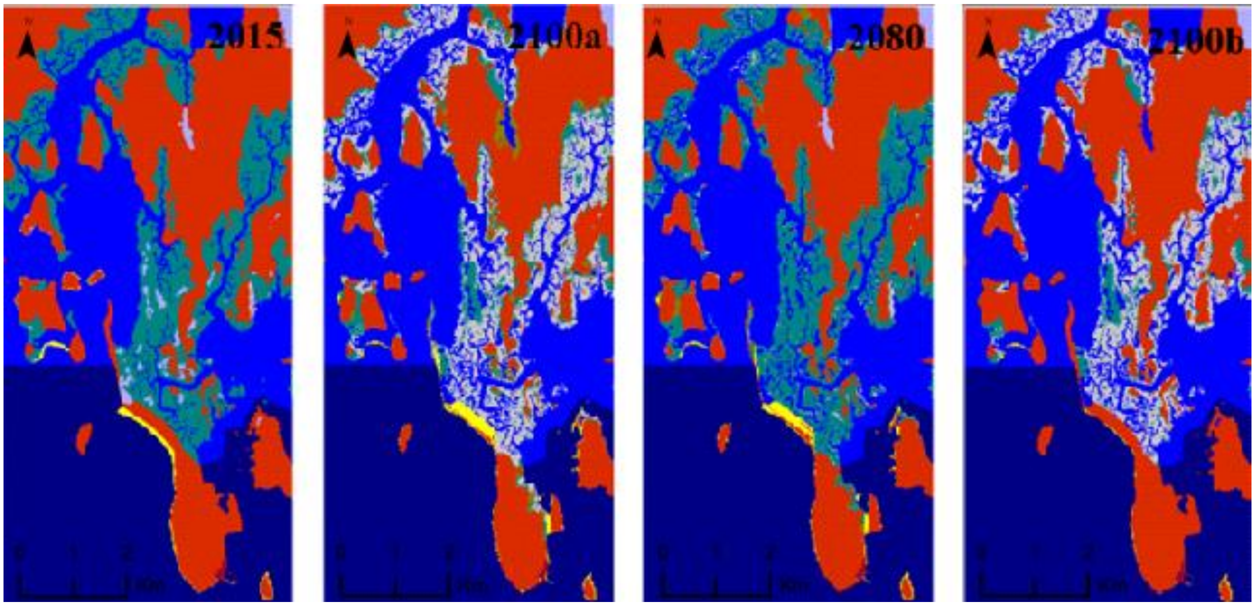


Figure 13 Pinkney's Point SLAMM model represented at time zero in 2015 and various scenarios in 2080 and 2100. 2100a represents a high sea-level rise scenario (1.4m) with unprotected dry land. 2080 and 2100b show the difference between 20 years in a high sea-level rise scenario protecting dry land.

Chapter 5: Discussion

5.1 Why it is Necessary and Value Provided

Even though there are no concrete conclusions that can be deduced from this report regarding long-term saltmarsh sustainability, it demonstrates that the methodology elaborated on would be effective at assisting in the prioritization of salt marshes in Canada. Even if this model only works at a high level, it can show how marshes will evolve and the amount of carbon they can sequester which can work in favour of future protection and restoration discussions (Wedding et al., 2021). The CBC tool was used during this investigation, but due to the current limitations of creating future land use rasters in SLAMM, the results are not applicable to the report. Moving forward, the requirements of modelling software, whether it is the CBC tool or something different, should be taken into account when collecting data to facilitate seamless integration. Collecting data and cataloging it in a consistent manner that is SLAMM-friendly can be a path towards creating a high-level inventory of the amounts of carbon in blue carbon ecosystems across Canada. Creating a centralized, high-level blue carbon database accessible to all would provide individual coastal managers with the resources necessary to utilize the SLAMM and CBC tools. Coastal managers could combine their local knowledge of hydrology, sediment delivery and subtler aspects of the area to aid in guiding future management efforts.

Providing these tools to local communities embraces a more bottom-up approach to coastal management with less reliance on governing body's intervention.

An unplanned outcome for the particular methodology used was that it became a resource to demonstrate outcomes about how the coastline could be shaped decades from now. Coastal planning initiatives such as integrated coastal zone management (ICZM), marine protected area (MPA) network planning and marine spatial planning (MSP) (if it extends its query into the intertidal zone) could see benefits. Currently, there is an effort to integrate climate change into MSP (Frazão Santos et al., 2020) and using this methodology to integrate the future outlook of the coastline and marshland, the protection or restoration of marshes can be adjoined with other planning efforts. Refining models such as SLAMM and the CBC tool can provide an interdisciplinary group of stakeholders an effective resource to gauge how infrastructure and marshes could be affected by sea-level rise and how carbon storage is impacted.

An additional rationale for implementing this methodology is that it helps bridge the gap between ad-hoc blue carbon research throughout Canada and the actionable protection and restoration of blue carbon ecosystems. The facilitation of knowledge transfer – or research to action contains numerous barriers due to jurisdictional boundaries, uncertainty and stakeholder conflict (Frazão Santos et al., 2020; Drever et al., 2021). While this methodology will not solve every issue, it can be added to a growing toolkit that can transcend conversations within the environmental community to provide guidance to governing bodies due to its quantitative nature.

5.2 Uncertainty and Risk

While the protection and restoration of blue carbon ecosystems such as salt marshes are not new, the conversation around the protection and restoration of these ecosystems, specifically for their carbon sequestration potential, is a relatively new phenomenon (Gulliver et al., 2020; Nahlik & Fennessy, 2016; Gailis et al., 2021). Many estimates that predict the spatial extent of marshes in the world and how much carbon they can store vary anywhere from 22,000 – 400,000 km^2 and 4.8-87.2 Tg C/yr (Chmura, 2013). The uncontrollable nature of the variables associated with carbon storage, sea-level rise, and marsh evolution build in inherent uncertainty and risk when attempting to define management plans (Fitzgerald & Hughes, 2019). Further, the same area's carbon storage can have vastly different accretion rates due to spatial variability (Chmura & Hung, 2004). Combined with present data constraints, it poses a unique set of obstacles, albeit surmountable ones, to the advancement of using blue carbon as a mitigation strategy (Wedding et al., 2021). The fundamental science of whether blue carbon can make a difference in mitigating CO_2 is unquestioned; the matter is by how much? Regardless, these barriers and knowledge gaps should not deter the active involvement of moving forward with blue carbon projects. The current gaps in policy, science and governance can be met through transparent communication, accurate monitoring, and successful projects (Macreadie et al., 2019).

Prioritizing blue carbon ecosystems for protection and restoration without having control over the many variables or exactly knowing what a successful result entails is an unsavoury thought for governments and other stakeholders. Even if there was greater understanding and control over variables, a natural disturbance risk could not be forecasted at the beginning of a management plan. However, the other side of this equation also applies in this situation. Research can continually be refined, and understanding can improve over the next few decades, but there will always be uncertainty due to climate change, anthropogenic effects, and ecosystems dynamism. Any progress could be stunted by the quest for perfect science, which in this scenario is highly unlikely. Acknowledgement of the realities, transparent communication between stakeholders and realistic objectives are crucial for future blue carbon protection and restoration planning. Additionally, active monitoring and adapting plans over time are a must due to the recognized imperfect science.

Sea-level rise, temperature and storm projections are supposed to stay relatively consistent until 2050 for the Gulf of Maine region (Chisholm et al., 2021), which allows for a certain amount of confidence in planning efforts. Post-2050, the uncertainty grows significantly and depends largely on the mitigation measures of the present (Chisholm et al., 2021). In a perfect world, the present and upcoming decades would be used for proactive planning, implementing mitigation strategies and lowering current emissions. This methodology can be integrated into future risk analysis. Visualizing how the coastline might change in one region versus another and the differences, where infrastructure will be affected, and if carbon storage is net-sequestered or emitted will help prioritize one project over another, especially when time and resources are limited.

Globally, climate change, sea-level rise, storms and the intense flooding they produce have created a cause for concern. The ripple effect from these events transcends the impacted coastal area at which it occurs. Concerns radiate within everyone, from government-level decision-makers to the people who have watched the ocean encroach on their waterfront property over the past decades. Eventually, a time will come for tough decisions contemplating what to protect, restore, and let go. This time has already come for some communities, such as the Big Lake community of East Chezzetcook, Nova Scotia, where it was deemed no longer cost-effective to continue to maintain its barrier beach that separates the communities freshwater lake and the ocean (CBCL, 2018). These decision-making processes are about as complex and difficult as they come with economic, social, cultural and environmental factors all involved and any tools such as this methodology that can help inform these decisions should be evaluated. Although this is a high-level tool, it can assist and be a part of a larger decision-making tree used to prioritize what areas should be a focus of protection or restoration. Thus, leading to decisions that have the best chances to help contribute to overall carbon emission reduction.

5.3 Canada's Paris Agreement Objectives

Recently, there has been a push to perform due diligence on how much impact blue carbon ecosystems can have on a country's carbon storage and sequestration goals (Sutton-Grier & Moore, 2016). This call has not come just from the scientific community but from the private sector, government, conservation authorities and international governing bodies (Macreadie et al., 2019). Canada ranks seventh globally for total CO_2 emissions by country and CO_2 emissions per capita (Crippa et al., 2021). If Canada wishes to uphold its responsibility to the Paris Agreement, some significant changes are required to become more sustainable. While it will take more than just protecting and restoring blue carbon ecosystems to hit these Paris targets in Canada, they play a diverse role due to the many ecosystem services they provide. Further, according to Carlson (2020)

> Canada is lagging behind other coastal countries, notably the United States and Australia, in assessing and managing blue carbon resources in coastal ecosystems. Because of this, we may miss opportunities to develop projects that have the 'triple win' of adaptation, mitigation and biodiversity protection. (p. 40)

In 2019, Canada achieved its commitment to the Convention on Biological Diversity’s Aichi Target 11, protecting at least 10% of its ocean and coastal areas (Government of Canada, 2020a). However, that commitment was reached through a combination of creating a few large MPAs and unconventionally by reclassifying fishery closures rather than a significant change in current practices (Lemieux & Gray, 2020). As a member of the High Ambition Coalition for Nature and People, and the Global Ocean Alliance, Canada has committed to protecting at least 30% of the ocean and coastal areas by 2030 (Government of Canada, 2020b). This will require significant progress in protecting new areas because this target will not as easily be reached by using political semantics. Various policymakers can utilize blue carbon in Canada to assist in guiding these commitments. As of writing, there are no Canadian federal or provincial regulations that are written explicitly for blue carbon and no nationwide inventory of blue carbon ecosystems (Carlson, 2020). However, several options of statues already exist in Canada that could assist in providing spatial protection to blue carbon ecosystems, such as the *Oceans Act, Canada National Parks Act and Canada National Marine Conservation Areas Act* (Carlson, 2020), in addition to a variety of provincial statues that offer protection of the environment.

There is optimism that blue carbon ecosystems can be a powerful negative emission technology for Canada and worldwide (Wylie, Sutton-Grier & Moore, 2016). However, this optimism needs to be endorsed by data that supports taking this initiative. There is a push to form a consensus among various stakeholders in Canada on how blue carbon should be tracked and by what metrics (Carlson, 2020), but NbCS like blue carbon ecosystems have several functions, making this not a straightforward task. Despite the complexity of tracking, there is a belief that they can improve biodiversity, assist in reaching SDG's (Wedding et al., 2021) and should be a part of the discussion to attain Canada's goal of 30% of their waters and coastal areas being protected by 2030. Recently, reports from COP26 discussed how Canada has to strengthen their policies to meet its NDC targets because they are not on track (UNEP, 2021). Working to incorporate the protection and restoration of blue carbon ecosystems into their policies could help close that gap.

6. How to Improve/Recommendations

Despite some limitations to using this methodology, FitzGerald & Hughes (2019) review of marsh responses to sea-level rise and climate change stressed the importance of future marsh modelling. Similar to what was found in this study, there are limitations with current parameter accuracy and demonstrating the relationships of the complex environments precisely. The caveat to recommending this methodology for general use in Canada is the significant amount of logistical work and data collection requirements necessary beforehand. Because data and the tools to analyze it change rapidly, this study is seen as a valuable outcome of an iterative process, which does, interestingly, match the overall processes in climate change research and action. While not a direct focus of this paper, it was evident when exploring software modelling techniques and data throughout Canada and the United States that there needs to be a greater focus on vertical datum consistency. In this report, a method is used to adjust datums to the mean tidal level in Canada. However, the accuracy is imperfect and not a reasonable long-term approach due to the time and manual manipulation required, should SLAMM be adapted in Canada. In the future, a possible way to validate the reliability of this methodology or something similar would be to follow the example given in Clough, Polacyzk & Propato (2016). They have validated SLAMM by utilizing retrospective analyses where it showed that coastal forest loss was predicted to be 35% by the model, whereas 39% actually occurred.

Another focus for Canada should be a centralized wetland inventory that various stakeholders can access. With the acceleration of sea-level rise looming and climate change, the coastal zones should be of particular focus for future mapping and monitoring. Specifying between high and low marsh and whether the data is attained at high, mid or low tide should be noted. These projects should collaborate with Canadian blue carbon fieldwork to address knowledge gaps, agree on consistent tracking metrics, and negate redundancy.

Modelling processes such as the one proposed are helpful in decision-making, but it is one piece to a much larger puzzle of managing blue carbon ecosystems and Canada's coastal zone. It should be recognized that this methodology cannot be used in isolation as quantifying carbon values does not provide a holistic approach to valuing wetlands. It can be used in affiliation with other research and stakeholder priorities to help solidify a decision-making strategy. The management decisions that will forge the direction of future coastlines require scientific backing and community involvement. It is necessary to consider the temperature of the stakeholders, rights holders and the community surrounding the blue carbon environment and how they perceive the problem. Depending on the composition of the coastline, whether it is primarily private or public land, factors in considerably for transparent and thoughtful planning.

This report has shown how SLAMM and the CBC tool can be valuable coastal decision-making tools, should the appropriate data be available. However, they do not encompass all possible carbon storage and sequestration realities because some are not included in this modelling equation. Out of the scope of this paper, but very much worth considering in future blue carbon work are Odum's outwelling hypothesis and coastal marsh migration leading to forest mortality (Santos et al., 2021). Outwelling is the process of salt marsh transporting carbon to the ocean by tidal exchange, and it is unknown if this carbon is remineralized and returned to the atmosphere as CO_2 or buried in the deep ocean (Figure, 14) (Santos et al., 2021). Most strategies to quantify and research blue carbon ecosystems are focused on the carbon in biomass and the underlying sediment. However, depending on the remineralization versus burial ratio, it is sensible to believe that blue carbon ecosystems could be the reason for greater or lesser carbon sequestration than previously accounted for should these pathways be investigated further. Another factor not considered is that as salt marsh migrates into forested areas, the salinity destabilizes the terrestrial ecosystem (Smith & Kirwan, 2021). The balance of loss of forest biomass, causing greater CO_2 emissions versus migration of salt marsh, which increases CO_2 sequestration, needs to be considered in applicable areas.

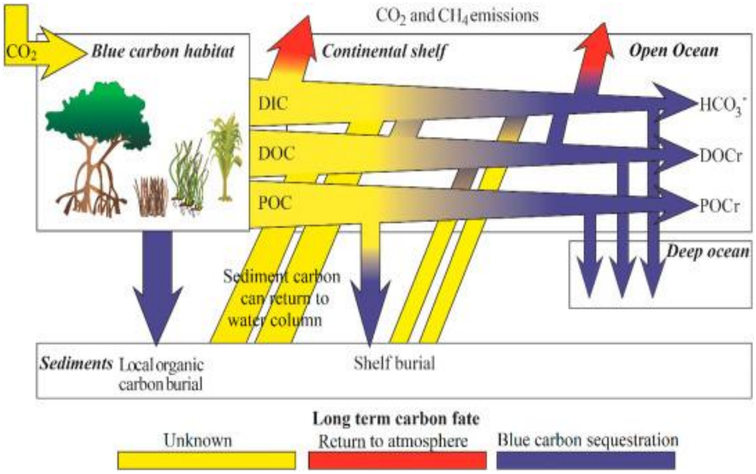


Figure 14 Potential blue carbon outwelling pathways for dissolved inorganic, dissolved organic and particulate organic carbon once they The chemical composition and transformations that the carbon undergoes compose a not fully understood mechanism for dictating whether the carbon ends up buried in the deep ocean or emitted as CO_2 *(Santos et al., 2020).*

6. Conclusion

Upon going through the process of using SLAMM and the CBC tool in a Canadian context, it is evident that should the appropriate data be available to do this type of analysis for blue carbon ecosystems throughout Canada, it can become a valuable piece to the coastal manager's toolkit. The vision for this work is that there would eventually come a time when data accessibility was not an issue, and local coastal managers could access a database and combine it with their local knowledge and ecosystem tracking to perform this type of methodology seamlessly. If possible, a high-level carbon storage quantification number for Canadian salt marshes would be accessible. By creating a quantifiable valuation of blue carbon ecosystems, it will assist in dictating future protection and restoration discussions.

The effort to measure total blue carbon throughout Canada needs to be a national effort, but the protection and monitoring of these ecosystems must be done at a local level. This point becomes even more salient when considering the varied nature of sea-level rise, storm surge and coastal erosion regionally. The awareness and desire of local communities to adapt to the threat of climate change and mitigate future impacts are prevalent, and coastal retreat is always a last resort option. The organization of both of these efforts is what is currently distorted. If this methodology or something similar can be successful at a local level, it can make the case to governing bodies that it should be deployed more widely. There would be ample benefits to this, among them creating a sense of empowerment within coastal communities believing they have support from the government and a little control over the uncertain future.

The process of highlighting blue carbon ecosystems in Canada for protection or restoration does not need to wait for something like this methodology to be ready to prove its worth. The science is clear; blue carbon ecosystems can play a role in Canada's carbon emission mitigation efforts. Despite the current risks and uncertainty in the field, the continual building of Canada's national wetland inventory, synchronization of vertical datums with modelling software and improving monitoring practices for marshes are imperative to move blue carbon research forward in Canada. What is shown in this report is a plausible avenue to consider when taking the next step in highlighting blue carbon ecosystems for protection and restoration in Canada.

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Appendix A

Creation of SLAMM inputs on ArcGIS Pro for Pinkney Point, Nova Scotia

Digital Elevation Model (DEM)

1. On ArcGIS Pro create bare earth lidar
   a) Download .las files from https://nsgi.novascotia.ca/datalocator/elevation/ (CGVD 2013)
   b) Used 25 .las files (5x5) (*check number)* and merged them into a las dataset using geoprocessing tool "Create Las Dataset."
   c) In las dataset settings, filter out all classification codes except ground.
   d) Geoprocessing tool: "Las Dataset to Raster."
   e) Geoprocessing tool: "Raster Calculator". Script: Con(raster layer" <0,0,"raster layer") to change all values less than 0 to 0.

   f) Used Geoprocessing tools: "Is Null" and "Con" to set NoData to 0
2. Adjusting Lidar data to align vertical datums
   a) Geoprocessing tool: "Raster to Point."
   b) Geoprocessing tool: "Add Geometry Attributes," select "point x-, y-, z- and m-coordinates under geometry properties
   c) Geoprocessing tool: "Add Surface Information," ensure "output property Z" is checked
   d) Geoprocessing tool: Calculate field – modify z values by -0.645

      **Rationale below.*

      Raster data is formatted to CGVD2013

      - "*CGVD2013 is approximately 60 cm above CGVD28 in NS. The actual value depends upon the location and varies by about 10 cm across the Province"* (GeoNova, 2016)

        Running approx. offset – (-0.6m)

      Raster data approx. in CGVD1928

- *"CGVD28 offset is -2.355 with respect to chart datum (LAT)"* (Government of Canada, 2021).

Running offset – (+1.755m)

Raster data approx. in LAT

LAT with respect to MTL is +2.57 (Government of Canada, 2021).

Final offset – (4.325m)

- The vertical datum chart from the station lines up pretty close to what CGVD28 is in Yarmouth. Also, 4.337-3.692 = +0.645.

e) Select by attribute: less or equal to -2 to isolate all coastal points and water and change to 0.

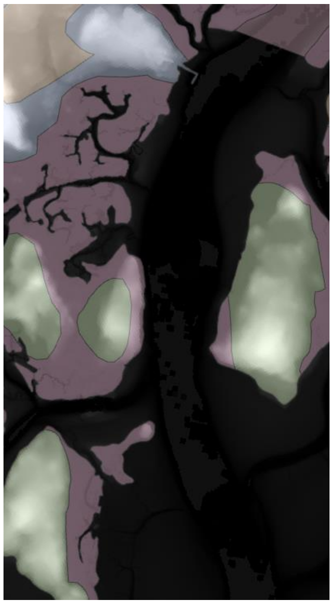
f) Geoprocessing tool: "Point to raster"

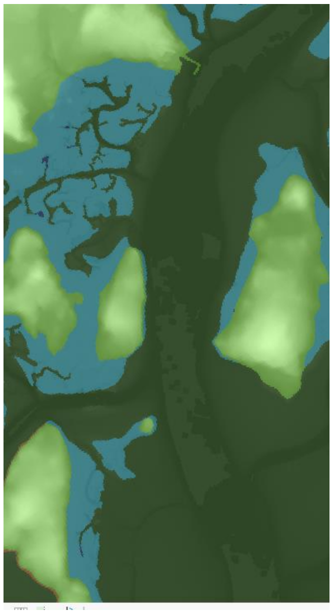
g) Geoprocessing tool: "Is Null" and "Con" (True raster = 0)

	Lidar CGVD2013 unchanged	CGVD1928 adjusted (approx.)
Salt Marsh	1.5m	0.9m
Water	-2.1m	-2.7m → 0 (manually adjusted)
Streams	-1.7m	-2.3m → 0 (manually adjusted)
Infrastructure	2.8m	2.2m

Creating Wetland Data inventory for SLAMM Inputs

1. Add 2015 Nova Scotia ecological classification from Open Data NS to Arcgis Pro.
2. Manual edits were performed using the DEM superimposed underneath the NS ELC data. Google earth engine was used as an additional delineation check. Example of the offset in the original data below to how it was changed.





3. Change ELC categories to SLAMM categories

SLAMM CODE	SLAMM Description	ELC 2015
1	Developed Dry Land	Manual Edits
2	Undeveloped Dry Land	Various
8	Regularly Flooded Marsh	Salt Marsh
11	Tidal Flat	Manual Edits
12	Ocean Beach	Manual Edits + Coastal Beach
15	Inland Open Water	Water
19	Open Ocean	Manual Edits

Slope Raster

a) Geoprocessing tool: "slope". Input: DEM raster.

** All files were resampled to a cell size of 5x5.

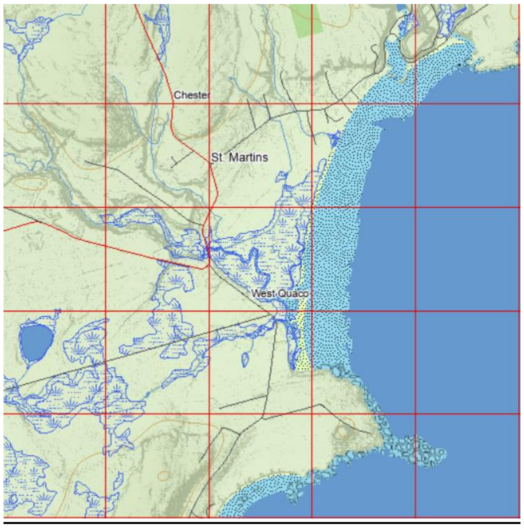
** All files were geoprocessed using “raster to ASC ll” as the final step before input into SLAMM

Appendix B

Creation of SLAMM inputs on ArcGIS Pro for St. Martins, New Brunswick

Digital Elevation Model (DEM)

1. On ArcGIS Pro create a bare-earth lidar
   a) Download .las files from https://geonb.snb.ca/li/ (CGVD 1928)
   b) Used 25 .las files (5x5) and merged them into a las dataset using geoprocessing tool "Create Las Dataset."



Additional information at https://geonb.snb.ca/arcgis/rest/services/GeoNB_SNB_LidarIndex/MapServer/9

   c) In las dataset settings, filter out all classification codes except ground.
   d) Geoprocessing tool: "Las dataset to raster."
   e) Geoprocessing tool: "Raster Calculator". Script: Con(raster layer" <0,0,"raster layer") to change all values less than 0 to 0.
   f) Used Geoprocessing tools: "Is Null" and "Con" to set NoData to 0.
2. Manipulate Lidar data to adjust vertical datum
   a) Geoprocessing tool: "Raster to Point."
   b) Geoprocessing tool: "Add Geometry Attributes," select "point x-, y-, z- and m-coordinates under geometry properties
   c) Geoprocessing tool: "Add Surface Information," ensure "output property Z" is checked

d) Geoprocessing tool: Calculate field - modify z values by -2.8. It was found that the streams running within the salt marsh in St. Martins were approximately 2.8m above 0. To normalize the data and align the water mark it was set to 0 to match the open ocean.

	Lidar CGVD1928 unchanged	CGVD1928 adjusted (approx.)
Salt Marsh	Approx. 4.1m to 4.3m	1.3 to 1.5m
Open Water	Approx. 0m to -4m	0m (manually adjusted)
Streams	Approx. 2.8m	0m (manually adjusted)

e) Select by attribute: less or equal to 0 to isolate all coastal points and water and change to 0.

f) Geoprocessing tool: "Point to raster"

Creating Wetland Data Inventory Raster

a) Add Wetland_2021 data and Ecological land classification (ELC) data 2018 (ecosites) from http://www.snb.ca/geonb1/e/DC/catalogue-E.asp to ArcGIS Pro.

b) Convert DEM to polygon by using the "Int" and "Raster to polygon" geoprocessing tools

c) Geoprocessing tool: "Clip" to align wetland_2021 and ELC data to the area of DEM polygon layer

d) Align attributes between Wetlands 2021 data and Ecosite 2018 data

- Add SLAMMCODE field to each attribute table

- Change all Ecosites to "2" for undeveloped dry land except site 6f (bottomland sites near flood plains and salt marsh. 6f turned into ocean beach
- For Wetlands_2021 Data

SLAMM CODE	SLAMM Description	Wetlands 2021 Data
2	Undeveloped Dry Land	Various ELC classes
3	Nontidal Swamp	Bog, Fen, Shrub Wetland and Forested Wetland
8	Regularly Flooded Marsh	Salt Marsh
12	Ocean Beach	6f, Manual Edits
15	Inland Open Water	Water
19	Open Ocean	Manual Edits

e) Geoprocessing tool: "Overlay layers." Input layer: wetlands_2021; Overlay layer: ecosite data; Overlay type: Union

f) Select attributes: Equal to Slammcode 2. Geoprocessing tool: "Merge." Also, manually merge overlapping Slammcodes 3 and 8

g) Using edit tools. "Clip" Select all attributes except Slammcode 2 as input features, then select slammcode 2 as target features. Discard.

h) Geoprocessing tool: "Polygon to raster."

i) Geoprocessing tool: "Extract by mask." Input: wetland data; Feature mask data: DEM raster

j) Geoprocessing tool: "Is null"; Geoprocessing tool: "Con" Input conditional raster: Null raster; Input true raster or constant value: 19 (SLAMM Open Ocean); Input: false raster

k) Extract by mask: wetland raster

Slope Raster

a) Geoprocessing tool: "slope." Input: DEM raster.

** All files were resampled to a cell size of 5x5.

** All files were geoprocessed using “raster to ASC ll” as the final step before input into SLAMM

Appendix C

Biophysical Inputs used in SLAMM for Yarmouth, Nova Scotia

The inputs for the salt line, MHHW, MLLW are all adjusted due to the vertical datum alignment and will not make sense if interpreted by referring to chart datum. Rationales and links are provided for inputs that are not default settings. Default setting information can be found in the "Notes" section below.

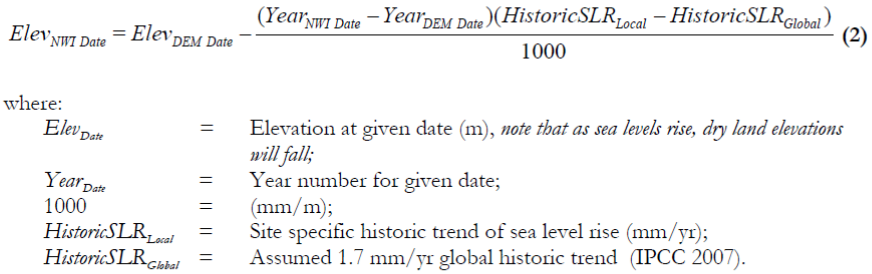
Biophysical Inputs

Case Study 1: Southwest, Nova Scotia (Pinkney's Point)

Sea-level rise estimates: The high and low estimates for sea-level rise in Yarmouth are used within the model and found on the Nova Scotia government website.
https://climatechange.novascotia.ca/sites/default/files/uploads/Yarmouth-climate-data.pdf
2025 – Low: 0.12cm, High: 0.18cm
2055 – Low: 0.28cm, High: 0.58cm
2085 – Low: 0.47cm, High: 1.19m
2100 – Low: 1.06m, High: 1.54m

NWI Photo Date: 2015
DEM Date: 2019

From SLAMM technical document: The NWI photo date and the date of the digital elevation model (NED) may differ. In an attempt to correct any temporal discrepancy in elevations due to land movement, NED data are converted to achieve the same temporal aspect as the NWI data:



$$Elev_{NWI\ Date} = Elev_{DEM\ Date} - \frac{(Year_{NWI\ Date} - Year_{DEM\ Date})(HistoricSLR_{Local} - HistoricSLR_{Global})}{1000} \qquad \mathbf{(2)}$$

where:

$Elev_{Date}$ = Elevation at given date (m), *note that as sea levels rise, dry land elevations will fall;*

$Year_{Date}$ = Year number for given date;

1000 = (mm/m);

$HistoricSLR_{Local}$ = Site specific historic trend of sea level rise (mm/yr);

$HistoricSLR_{Global}$ = Assumed 1.7 mm/yr global historic trend (IPCC 2007).

○

Direction Offshore: South

Historic trend (mm/yr) – 3.6mm (Han et al., 2013)

https://www.erudit.org/en/journals/gpq/1900-v1-n1-gpq1903/032950ar.pdf

Eustatic trend – 3.2mm (von Schuckmann, K., et al., 2019). Copernicus Marine Service Ocean State Report

https://internal-journal.frontiersin.org/articles/10.3389/fmars.2019.00234/full

Mean Tidal Level (MTL)-NAVD88 (m) = 0 (Datum set to MSL within Arcgis Pro)

GT diurnal tide range – I have it set to 1.15 to match where MHHW would be in comparison to the adjusted salt line. (MHHW at 1.15 – approx. 0 (MLLW) = 1.15

Salt Line above Marsh (m above MTL) - "Salt marshes which occur at a narrow elevation range spanning mean high water" (Chmura & Hung, 2004). However, for this model I set it to 0.8m, just below the where the CGVD1928 MTL marsh is set too.

Marsh Accretion (mm/y) – "The depth of the fallout peak in cores CH1 b, CH4 and CH2b suggests an estimated" mean accretion rate of 2.8 mm/yr in the middle marsh and 3.6 mm/y in the high marsh for the last 30 years". Regular flood marsh accretion – 2.8mm/y and irregular flood marsh accretion – 3.6mm/yr.

https://dalspace.library.dal.ca/bitstream/handle/10222/35385/NSIS_v41_p4_a2_Cahgue-Gofp_C_Geochemical_Evidence_For_The_Recent_Changes_In_A_Salt_Marsh_Chezzetcook_Inlet_Nova_Scotia_Canada.pdf?sequence=1

Salt Marsh erosion (horz. m/yr) – 1 (default)

Tidal Flat Erosion (horz. m/yr) – 0.85m/yr. Currently using scarp retreat as a proxy for tidal flat retreat. "Dunn's Beach the rate of scarp retreat has varied from 0.27 to 0.85 m/yr, depending on the time period and the location on the drumlin. This gives an average erosion rate of 0.5 m/yr since 1939, with maximum rates recorded of 0.85 m/yr between 1997 and 2007. This compares with an average erosion rate for the coast near Amherst of 0.4 m/yr" (Utting & Gallacher, 2008) https://novascotia.ca/natr/meb/data/pubs/09re01/09re01_20Utting.pdf

Marsh Erosion Fetch (km) = Is set at 21km because SLAMM inundation model changes developed dry land to the estuarine beach when adjacent to water when fetch is greater than 20km.

Beach Sedimentation rate (mm/yr) = 1 (default)

Notes:

[1] There was a dike built manually within the SLAMM model to protect Melbourne Road.

[2] Default settings information at: https://docs.google.com/spreadsheets/d/13AhT1PwsUsmOSA3LdGTtbWZIBIk1DoZ7D7KCheGlXtk/edit#gid=0

Appendix D

Creation of SLAMM inputs on ArcGIS Pro for St. Martins, New Brunswick

Rationales and links are provided for inputs that are not default settings. For information on default settings, see Appendix C.

Biophysical Inputs

Case Study 2: St. Martins, New Brunswick

Sea-level rise estimates: The high and low estimates for sea-level rise in St. Martins that are used within the model. https://www.csrpa.ca/wp-content/uploads/2017/11/sea_level_rise_estimates_for_nb_municipalities.pdf

2025 – Low: 0.09cm, High: 0.15cm
2055 – Low: 0.28cm, High: 0.52cm
2085 – Low: 0.48cm, High: 1.04m
2100 – Low: 0.57m, High: 1.33m

NWI Photo Date: 2018 (ELC) 2021 (Wetland) http://www.snb.ca/geonb1/e/DC/catalogue-E.asp
DEM Date: 2013
Direction Offshore: South
Historic trend (mm/yr) – 2.2mm (Han et al., 2013)
Eustatic trend (mm/yr) - 3.2mm (von Schuckmann, K., et al., 2019). Copernicus Marine Service Ocean State Report (1993-2007) https://internal-journal.frontiersin.org/articles/10.3389/fmars.2019.00234/full

Mean Tidal Level (MTL)-NAVD88 (m) = 0 (Datum set to MSL within ArcGIS Pro)

GT diurnal tide range (m) – MHHW-MLLW 3.86 – (-3.95) = 7.81 https://www.qc.dfo-mpo.gc.ca/tides/en/stations/00129/2021-07-19?tz=UTC . However, I have it set to 5.01m because 7.81-2.8 = 5.01m. (-2.8m was the vertical datum adjustment)

Salt Elev. (m above MTL) – 9.14 – 5.28 = 3.86. https://www.qc.dfo-mpo.gc.ca/tides/en/stations/00129/2021-07-19?tz=UTC However, for this model I set it to 1.06m, just below the where the CGVD1928 MTL marsh is set too.

Marsh Accretion (mm/yr) - 1.6mm/yr. Used an accretion rate found in Little Lepreau as a proxy. http://bgc.seas.harvard.edu/assets/chmura2001.pdf

Tidal Flat Erosion (horz. m/year) – 0.5 (default)

Salt marsh erosion (horz. m/year) – 2 (default)

Swamp erosion (horz. m/year) – 1 (default)
https://www.sciencedirect.com/science/article/pii/S1364815216302705#fig4

Swamp accretion (mm/year) – 0.3 (default)

Marsh Erosion Fetch (km) = Is set at 21km because SLAMM inundation model changes developed dry land to the estuarine beach when adjacent to water when fetch is greater than 20km.

Beach Sedimentation rate (mm/yr) = 1 (default)