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Valuing the Salt Marsh Ecosystem: Developing Ecosystem Accounts

by Tasha Rabinowitz and Jessica Andrews

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1. Introduction

Increasing concern about the economic, social and health risks to Canadian communities resulting from climate change and biodiversity loss have led to the creation of the Census of Environment (CoE) (Statistics Canada, 2022). This new program will report on ecosystems in Canada, providing information to help Canadians make evidence-based decisions to protect, rehabilitate, enhance and sustain our environment.

Using the United Nations System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA–EA) framework (United Nations et al., 2021), the CoE will develop comprehensive ecosystem accounts to help track changes in extent, condition, and ecosystem services provided by ecosystems over time (Figure 1). These accounts will help to bridge the gap between economic and environmental data for policymakers. By bridging this gap and placing an emphasis on the value of the natural environment and its benefits to society the accounts will support analysis of benefits and trade-offs between the economy and environment.

Over time, the CoE will develop ecosystem accounts for many ecosystem types in Canada. One of the early focal areas for the CoE will be salt marshes, a coastal ecosystem. Although Canada has the longest coastline in the world, data on coastal ecosystems are generally lacking, as the focus of data collection is typically on ecosystems that are traditionally recognized as economically valuable. However, there is growing recognition of the importance of coastal ecosystems such as salt marshes for climate change adaptation and mitigation.

Salt marshes provide valuable ecosystem services including but not limited to carbon sequestration, protection against coastal storms and flooding, maintenance of water quality and quantity, habitat provision and support of recreational activities. Moving forward, data collection about these ecosystems is important because they are vulnerable to the impacts of climate change (Lemmen et al., 2016) and are at risk of being lost along with their services.

This publication marks the beginning of ongoing research and partnership creation which will inform the development of pilot salt marsh accounts. In this paper, an ecosystem accounting framework for Canada's salt marshes is presented. The framework has been intentionally created with flexibility in mind so that other groups can use and adapt it to their specific needs. Over the next year this framework will be used to begin producing these accounts, leading to a growing number of tables and other data products. As accounts continue to be developed over the years in collaboration with different levels of government, industry, Indigenous groups and NGOs, data sources and methodology of data collection and analysis will be refined. Through this process, account tables will be continually expanded and updated using data from multiple sources, simple models, and through engagement with experts.

Ideally, accounts along with additional associated information would be produced on an annual basis, however, more research and data are required to reach this goal. The first pilot accounts will be compiled opportunistically and will reflect the knowledge and data gaps described in this paper, with some variables missing, incomplete, roughly estimated, or presented using proxies.

The first section of this paper briefly outlines salt marsh extent. The following sections focus on condition and ecosystem services accounts, including proposed variables, methodology, metrics data sources, challenges and limitations. This technical paper provides a foundation for the development of salt marsh accounts and will serve as guidance for the further development of coastal and ocean ecosystem accounts as part of the CoE, which will ultimately provide a full picture of the state of ecosystems and their contributions to Canadians.

Figure 1
Key components in the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA–EA) framework

① **Extent:**
The extent account tracks change in the area covered by different ecosystems. For example, the boundaries of individual salt marshes are measured repeatedly to understand changes in extent.

② **Condition:**
The condition account compiles information about the health of ecosystems. For salt marshes, that means tracking characteristics such as the duration of tidal flooding at individual marshes.

③ **Ecosystem services:**
Information from the extent and condition accounts informs the measurement of ecosystem services. An important service provided by salt marshes is coastal protection. Healthy salt marshes that are not shrinking can protect homes and infrastructure from coastal flooding.

What are salt marshes?

The International Union for Conservation of Nature (IUCN) Global Ecosystem Typology is the proposed SEEA–EA reference classification for delineating ecosystems. It classifies coastal river deltas, intertidal forests, and coastal salt marshes as distinct ecosystem functional groups within the brackish tidal biome (Keith et al., 2020).

Salt marshes are a type of coastal wetland that occur globally in middle to high latitudes, typically along sheltered coastlines and in estuaries (McOwen, et al., 2017). They are found in the upper intertidal zone between mean sea level and high tide where salt- and flood-tolerant vegetation is able to live. Depending on where a salt marsh is situated in relation to the ocean, overall salinity levels can vary. For the purposes of Statistics Canada's pilot salt marsh accounts, any tidally influenced marshes that are not solely influenced by freshwater are considered salt marshes.

Salt marshes have relatively flat topography with channel systems that allow tidal flooding. At high or extreme high tide, the entire marsh surface can be flooded. Salt marshes can also have depressions in the surface called 'pannes' where water pools (French, 2019). Intermittent tidal flooding and salinity are characteristic of these ecosystems and produce fine-scale hydrological and salinity gradients across the marsh surface (Keith et al., 2020). These gradients affect the organization of plant communities and overall functioning of the ecosystem (Pennings & Bertness, 2001).

Despite flooding and salinity stress, salt marshes support highly productive stress-tolerant grass-like plants (gramminoids), herbs and low shrubs (McOwen et al., 2017). Salt marsh vegetation plays a strong role in stabilizing marsh soils and facilitating marsh establishment and growth (French, 2019; Mudd et al., 2010; Van Eerdt, 1985). Since salt marshes are sedimentary systems, with enough available sediment they can grow vertically to adapt to sea-level and coastal condition changes, making them an excellent coastal climate change defense (Grenfell et al., 2019; Schile et al., 2014).

Salt marshes provide important ecosystem services including, but not limited to, carbon sequestration, protection against coastal storms and flooding, water quality and quantity maintenance, habitat provision and support of recreational activities. These services play a clear role in the well-being of Canadians, the Canadian economy and efforts to meet Intergovernmental Panel on Climate Change targets. They are also an important link between land and marine environments (Jänes et al., 2020), supporting industries such as commercial fishing. As such, they have been targeted as one of the first ecosystems for building ecosystem accounts as part of the new Census of Environment (Statistics Canada, 2022).

2. Applying the SEEA–EA in Canadian salt marshes

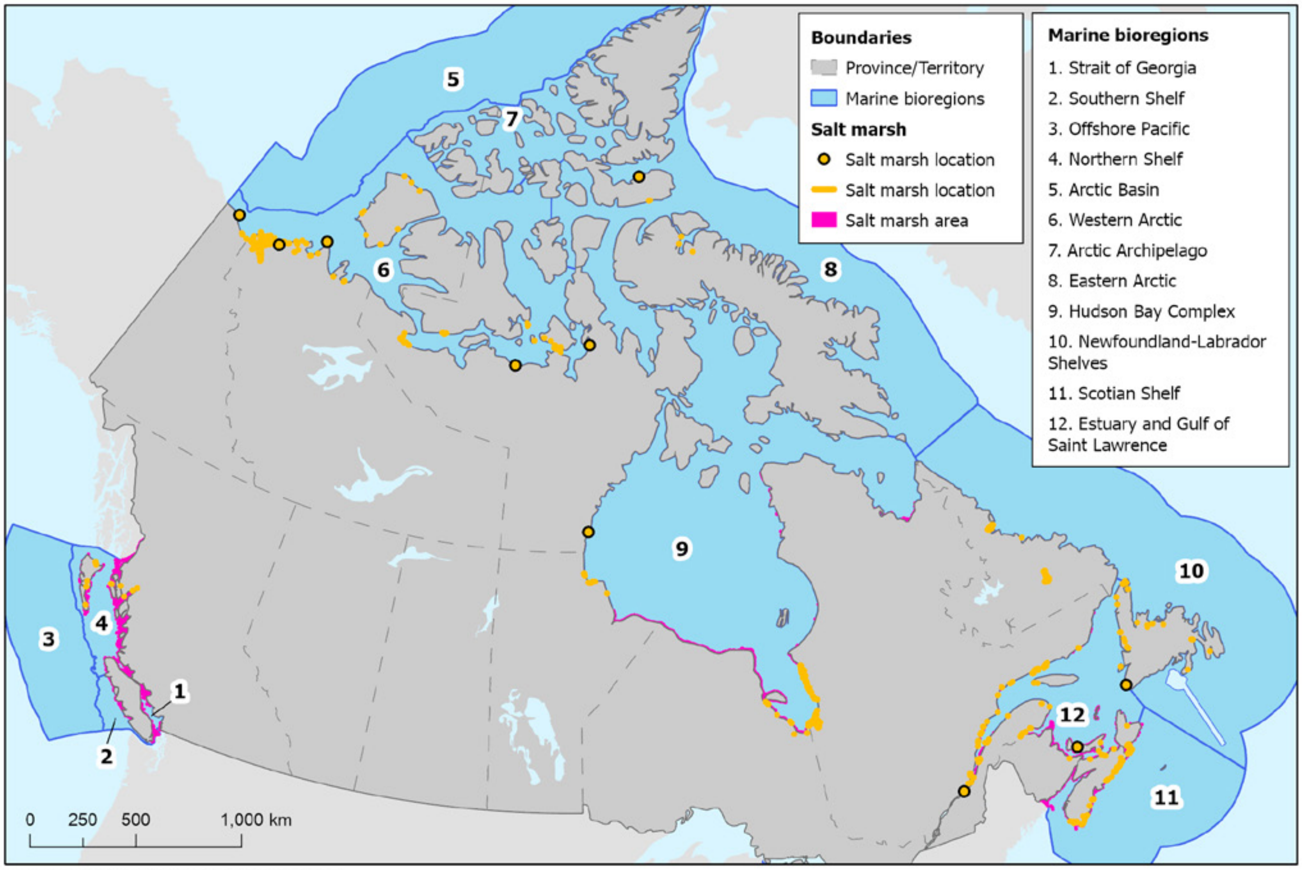
2.1 Extent

As salt marshes have not been comprehensively mapped in Canada, extent estimates (Table 1) were compiled using the best available data (see Appendix A for methods). Datasets include global, provincial and federal sources that span a period from 1995 to the present. Data were mainly acquired through remote sensing and satellite imagery, with some being ground-truthed by the collecting organizations. Together, these data cover most of the country (Map 1 & Map 2). Notably, there is a paucity of extent data in the North and in Newfoundland and Labrador where, at best, there are confirmed occurrences (denoted by points or lines on Maps 1 & 2) with no explicitly mapped area. Most regions with no explicitly mapped extent reflect data gaps as opposed to a lack of salt marsh. With better satellite data and land cover classification methods becoming available, data precision will improve and data gaps will be filled over time. Current estimated extent includes 3,602 km^2 of salt marsh area across the country, with an additional 1,304 km of coastline classified as salt marsh with no associated area.

The temporal coverage of these data presents several issues. First, the data provide a poor historical benchmark for salt marsh extent. There is an extensive history of marsh conversion to agricultural land in Canada. Converted marshes were used by early colonial settlers as farmland, especially the Acadians (dating back to the 1600s)

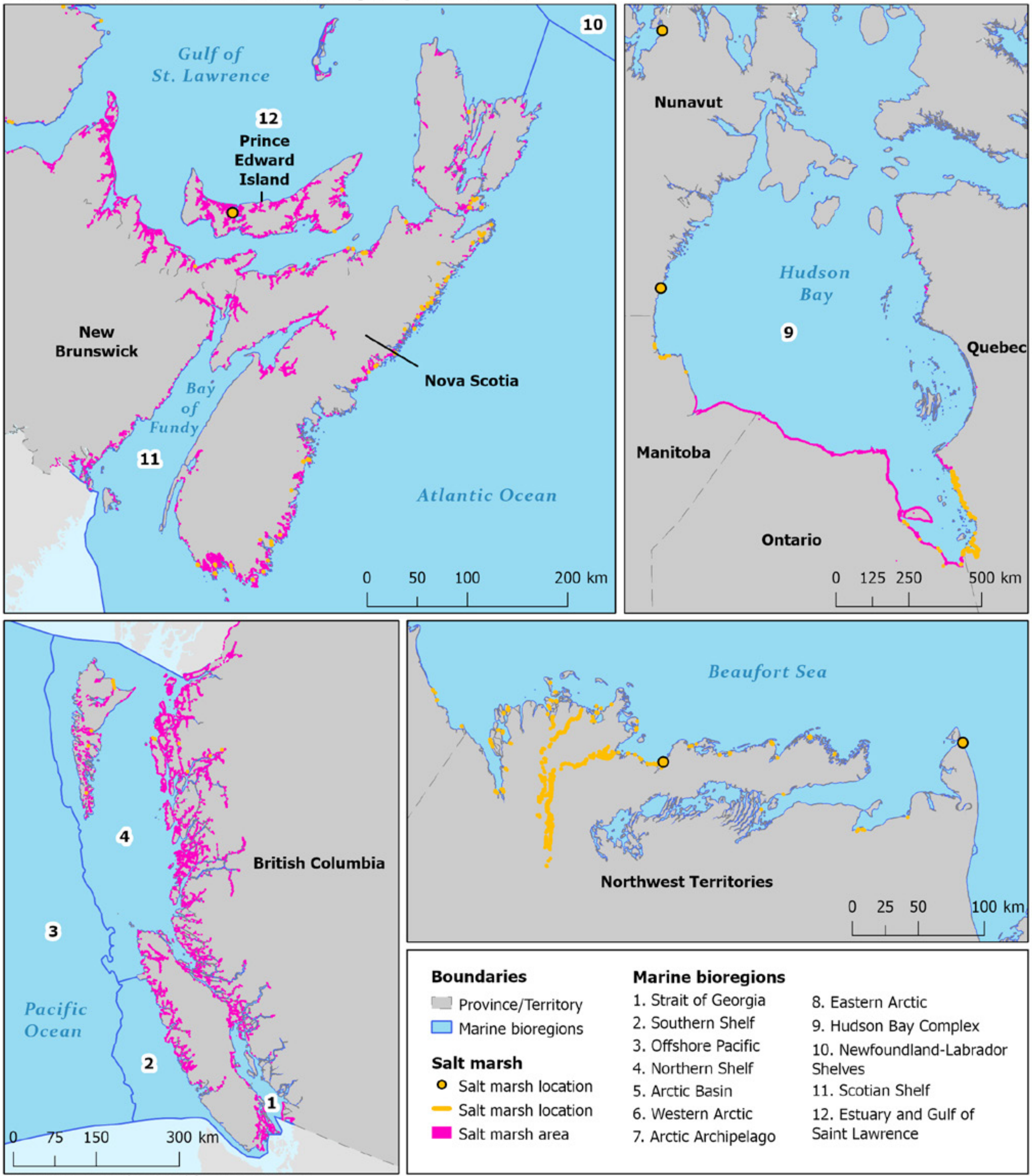
(Milligan, 1987). This issue is particularly noted in parts of the country where solely modern datasets are available. Second, use of a static extent does not allow tracking extent changes resulting from the natural processes of migration and erosion (see section 2.2.1.1), marsh changes from climate change, marsh change and loss due to construction, and extent gains from increasingly frequent restoration projects. These issues present a challenge for the compilation of extent accounts. They dictate a need to delineate salt marsh ecosystem boundaries on an ongoing basis to capture extent changes, which may be possible through remote sensing (e.g., Lopes et al., 2020; National Oceanic and Atmospheric Administration: Office for Coastal Management, n.d.). As such, regular updates will be made to salt marsh extent accounts as new data are available.

Map 1
Canadian salt marsh extent, 2022



Note: Data cover the period from 1995 to 2021.
Sources: Department of Environment and Local Government New Brunswick, 2021. Wetlands. *GeoNB*; Department of Fisheries and Oceans, 2016. Federal Marine Bioregions. *Open Data Canada;* Department of Fisheries and Oceans, 2018. Marsh inventory in the Chaleur Bay, Estuary and Gulf of St. Lawrence. *Open Data Canada*; Environment and Climate Change Canada, 2017. Atlantic shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. North coast of British Columbia shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. Northern Canada shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. Ontario shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. Québec - Saint-Lawrence river - shoreline classification. *Open Data Canada*; GeoBC, 2011. Shorezone observed habitat polygons. *British Columbia Data Catalogue*; Land Information Ontario, 2009. Far North land cover (v1.4). *Ontario GeoHub*; McOwen CJ, et al., 2017. A global map of saltmarshes (v6.1). *Biodiversity Data Journal* 5: e11764; Ministère des Forêts, de la Faune et des Parcs, 2017. Végétation du Nord québécois. *Données Québec*; Nova Scotia Department of Natural Resources, 2018. Ecological Land Classification 2015. *Nova Scotia Geographic Data Directory*.

Map 2
Canadian salt marsh extent by region, 2022



Note: Data cover the period from 1995 to 2021.

Sources: Department of Environment and Local Government New Brunswick, 2021. Wetlands. *GeoNB*; Department of Fisheries and Oceans, 2016. Federal Marine Bioregions. *Open Data Canada;* Department of Fisheries and Oceans, 2018. Marsh inventory in the Chaleur Bay, Estuary and Gulf of St. Lawrence. *Open Data Canada*; Environment and Climate Change Canada, 2017. Atlantic shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. North coast of British Columbia shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. Northern Canada shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. Ontario shoreline classification. *Open Data Canada*; Environment and Climate Change Canada, 2017. Québec - Saint-Lawrence river - shoreline classification. *Open Data Canada*; GeoBC, 2011. Shorezone observed habitat polygons. *British Columbia Data Catalogue*; Land Information Ontario, 2009. Far North land cover (v1.4). *Ontario GeoHub*; Mcowen CJ, et al., 2017. A global map of saltmarshes (v6.1). *Biodiversity Data Journal* 5: e11764; Ministère des Forêts, de la Faune et des Parcs, 2017. Végétation du Nord québécois. *Données Québec*; Nova Scotia Department of Natural Resources, 2018. Ecological Land Classification 2015. *Nova Scotia Geographic Data Directory*.

Table 1
Canadian salt marsh extent, 2022

	Area	Length	Point
Marine bioregion	km^2	km	count
Strait of Georgia	95	..	..
Southern Shelf	78	..	..
Northern Shelf	635	7	..
Western Arctic	..	382	5
Eastern Arctic	..	2	1
Hudson Bay Complex	2,271	429	1
Newfoundland-Labrador Shelves	..	171	..
Scotian Shelf	214	99	..
Estuary and Gulf of Saint Lawrence	309	214	3
Total	**3,602**	**1,304**	**10**

.. not available for a specific reference period
Note: Polygon data cover the period 1995 to 2021. Polygon area, lines and point extents are distinct areas of salt marsh.
Sources: Department of Environment and Local Government New Brunswick, 2021. Wetlands. Retrieved January 28, 2022 from http://www.snb.ca/geonb1/e/DC/catalogue-E.asp; Department of Fisheries and Oceans, 2016. Federal marine bioregions. Retrieved January 26, 2022 from https://open.canada.ca/data/en/dataset/23eb8b56-dac8-4efc-be7c-b8fa11ba62e9; Department of Fisheries and Oceans, 2018. Marsh inventory in the Chaleur Bay, Estuary and Gulf of St. Lawrence. Retrieved January 28, 2022 from https://open.canada.ca/data/en/dataset/49d8622c-e42b-4d8a-840d-c50b10e710c6; Environment and Climate Change Canada, 2017. Northern Canada shoreline classification. Retrieved January 25, 2022 from https://open.canada.ca/data/en/dataset/1c61d457-4d03-4f3a-9005-9aabb5a201bb; Environment and Climate Change Canada, 2017. North coast of British Columbia shoreline classification. Retrieved January 25, 2022 from https://open.canada.ca/data/en/dataset/09051eee-c28a-4746-8033-8e85815f4c73; Environment and Climate Change Canada, 2017. Atlantic shoreline classification. Retrieved January 25, 2022 from https://open.canada.ca/data/en/dataset/30449352-2556-42df-9ffe-47ea8e696f91; Environment and Climate Change Canada, 2017. Ontario shoreline classification. Retrieved January 25, 2022 from https://open.canada.ca/data/en/dataset/27515ccc-0cad-4f7d-b8ab-2a909090f128; Environment and Climate Change Canada, 2017. Québec - Saint-Lawrence river - shoreline classification. Retrieved January 25, 2022 from https://open.canada.ca/data/en/dataset/ba580518-59e8-4d1c-b3ef-41d2658e6965); GeoBC, 2011. Shorezone observed habitat polygons. Retrieved January 25, 2022 from https://catalogue.data.gov.bc.ca/dataset/shorezone-observed-habitat-polygons; Land Information Ontario, 2009. Far North land cover (v1.4). Retrieved January 28, 2022 from https://geohub.lio.gov.on.ca/documents/lio::far-north-land-cover/about; McOwen CJ, et al, 2017. A global map of saltmarshes (v6.1). Biodiversity Data Journal 5: e11764. Paper DOI: https://doi.org/10.3897/BDJ.5.e11764, Data retrieved January 28, 2022 from DOI: https://doi.org/10.34892/07vk-ws51; Ministère des Forêts, de la Faune et des Parcs, 2017. Végétation du Nord québécois. Retrieved January 25, 2022 from https://www.donneesquebec.ca/recherche/dataset/vegetation-du-nord-quebecois; Nova Scotia Department of Natural Resources, 2018. Ecological land classification 2015. Retrieved January 28, 2022 from https://nsgi.novascotia.ca/gdd/

2.2 Condition

Using the SEEA–EA framework, a set of accounting variables was developed to describe salt marshes' long term 'typical behaviour' and show changes over time (United Nations et al., 2021). Following the SEEA–EA ecosystem condition typology (United Nations et al., 2021), at least one variable in each category is proposed here to comprehensively describe salt marsh condition (Table 2). These variables were selected according to criteria outlined in Annex 5.1 of the SEEA–EA, which ensure the variables are conceptually appropriate, reasonably feasible, comprehensive and parsimonious.

The chosen variables are described in this section to varying levels of detail. Ecological relevance, potential data sources and methods, limitations and data gaps, and proposed options for metrics are discussed. Metrics may also include suggested proxies where direct measurements are difficult or impossible to obtain. When applying this framework, changes will be measured on a per-marsh basis as much as possible. As these accounts develop, the variables and metrics herein may be aggregated into ecosystem condition indices.

When the accounts are produced, supplementary tables will also be presented which will assist with the interpretation of ecosystem condition change. Supplementary tables will include data about positive and negative influences on salt marshes. Data on relevant climate variables (e.g., air temperature, sea surface temperature and salinity, precipitation, and days below freezing) and positive human modifications (e.g., invasive species management, intentional salt marsh restoration or creation, Indigenous management practices and legislative protection) are also to be included.

Table 2
Proposed variables for salt marsh condition accounts, grouped by SEEA–EA ecosystem condition typology

Group	Class	Variable
A: Abiotic ecosystem characteristics	A1: Physical state	Marsh surface elevation change (accretion, erosion, water channels, depressions)
		Tidal hydrology
	A2: Chemical state	Salinity
		Pollution
B: Biotic ecosystem characteristics	B1: Compositional state	Vegetation community patterns (dominant and invasive species, zonation)
		Animal biodiversity (native and invasive species)
	B2: Structural state	Vegetation structure (stem density, biomass)
	B3: Functional state	Disturbance events (wrack, ice, herbivory)
C: Landscape level characteristics	C1: Landscape and seascape characteristics	Tidal barriers and restrictions
		Surrounding land uses
		Landscape configuration

2.2.1 Physical state

Physical state variables describe the abiotic (non-living) components of an ecosystem in a physical manner (United Nations et al., 2021). For salt marshes, these include changes to marsh surface elevation and characteristics of tidal flooding.

2.2.1.1 Marsh surface elevation change (accretion, erosion, water channels and depressions)

Several processes interact to determine whether marsh surface elevation relative to mean sea level increases or decreases (French, 2019). Above ground, organic and inorganic materials (e.g., sediment and plant matter) are deposited onto (termed accretion) or eroded from the marsh surface (Neubauer, 2008). Below ground, decomposition and compaction occur, and roots and rhizomes contribute organic matter to the soil. These above and below ground processes can also be affected by sea-level changes and climate change (Chmura & Hung, 2004; Reed, 1995). The relative importance of above and below ground processes varies among marshes.

In ideal conditions, salt marshes respond to coastal changes such as sea-level rise through landward migration (horizontal growth) and accretion (vertical growth), which maintain an appropriate elevation relative to mean sea level for vegetation's survival when sediment availability is adequate (Butzeck et al., 2015; French, 2019). Landward migration is captured in the extent account, while surface elevation changes resulting from accretion or erosion are captured in the condition account.

Any changes in the processes that underlie accretion, such as changes in sediment supply (e.g., negative changes from construction of coastal protection structures and sediment mining or positive changes from increased primary production), can disrupt the balance and affect marsh topography and hydrology (Mudd, 2011; Schile et al., 2014). These changes to marsh function in combination with accelerated sea-level rise, can result in worsened marsh condition or loss of extent (FitzGerald & Hughes, 2019).

Marsh surfaces can also undergo localized surface changes such as expansion or erosion from the marine edge (Gabet, 1998; Houttuijn Bloemendaal et al., 2021), and migration or infilling of channels and pannes (Hughes et al., 2009). While expansion and erosion from the marine edge are captured in the extent account, migration and infilling or channels or pannes are captured in the condition account. These types of changes to water channels can affect the channel network configuration, impacting marsh hydrology and access by fish. Tracking these marsh surface changes provides information on the persistence of marshes and can signal changes to ecological functioning.

To measure marsh surface change, digital elevation models (DEMs; digitized models of the Earth's surface) are needed. Ideally, DEMs would cover Canada's entire coast, be collected long-term on a repeated basis and be of adequate horizontal and vertical accuracy. DEMs can be produced from locally collected data or from satellite data. Light detection and ranging (LiDAR) (Hladik et al., 2013), synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) instruments in particular show promise for DEM creation and surface elevation change measurement (Da Lio et al., 2018). Local DEMs are costly to produce but are typically more accurate. Creating DEMs from local or satellite data is difficult in salt marshes because of wet soils, dense vegetation and intermittent flooding. Aside from elevation change over the entire marsh surface, several measures of channel network configuration can be drawn from DEMs including, but not limited to, channel density and sinuosity (how winding a water channel or network is), which may be a useful metric of condition.

As a starting point for ecosystem accounts, options for creating summary information of present salt marsh elevations are being assessed. Over time, obtaining repeated DEMs will allow measurement of the rate of spatially-explicit elevation change, which is a more useful metric for assessing marsh condition.

Proposed metrics:

- Total area within specified elevation ranges
- Proportion of marsh area or total marsh area with elevation change outside a specified normal range over a period of time
- Number of marshes with average elevational change outside a specified normal range over a period of time
- Average elevation change (per unit area) relative to local sea-level rise estimate
- Channel network change (e.g., sinuosity, density)

2.2.1.2 Tidal hydrology

In salt marshes, tidal hydrology (specifically flooding) is intrinsically linked with the zonation of vegetation communities (Pennings & Bertness, 2001), access by animals and maintenance as a wetland. In salt marshes, three tidal hydrology characteristics are important: inundation duration (hydroperiod), inundation frequency and flood depth. Marsh hydrology changes occur with sea-level changes, or with the construction or removal of tidal barriers that stop or alter flooding (see section 2.2.6.1). Increases in flooding duration, frequency or depth can result in salt marsh vegetation drowning, causing marsh loss (e.g., panne expansion, conversion to mudflat or marine habitat) (Kirwan et al., 2010) and creating the potential for decreased carbon storage and sequestration from loss of vegetation (Payne et al., 2019). Decreases in flooding duration, frequency or depth can allow terrestrial vegetation to invade, causing conversion to terrestrial habitat (e.g., Smith & Warren, 2012). In the latter case, salt marshes may also change from a carbon sink to a source (McLeod et al., 2011) as soils become more oxygenated and decomposition rates increase. For these reasons, tracking marsh hydrology will help identify areas where plant communities and marsh function are changing, or where extent is likely to be lost.

Characteristics of tidal hydrology can be measured using tidal height data with DEMs to create simple flood models. Metrics describing tidal flooding can be created if the height of the tide relative to the height of the land is known. Reconciling tidal heights with land elevations is difficult because land and tidal elevations use different zero benchmarks, which also vary geographically. Ideally, a spatially-continuous tidal model that can be reconciled with a land datum is needed to produce meaningful data reflecting salt marsh tidal hydrology at a national level. In the absence of such a tidal model, use of data from the Canadian Hydrographic Service (CHS) may be an option. The CHS collects tidal height data at a limited network of stations across Canada. However, these point measurements are difficult to use in a spatially-explicit framework as they do not provide enough spatial coverage. Additionally, they are typically measured on the open ocean, whereas salt marshes develop in estuaries and along sheltered coastlines where tidal forces can be very different. At this time, options for producing meaningful statistics about tidal hydrology using sea-level rise data are being explored.

Proposed metrics:

- Proportion or total marsh area flooded with specified ranges of tidal heights
- Inundation frequency (percentage of high tides that cause flooding over a specified proportion of marsh area)
- Inundation time (average number of minutes a specified proportion of marsh area is flooded per high tide/ day/other unit of time)
- Duration (total time (minutes/days) a specified proportion of marsh area is flooded over a time period like year)
- Sea-level rise estimates over time

2.2.2 Chemical state

Chemical state variables describe the chemical composition of various parts of an ecosystem (United Nations et al., 2021). Important chemical components of salt marshes are soil and water salinity, and pollution concentrations in the soil and water.

2.2.2.1 Salinity

Salinity is a main abiotic characteristic linked to salt marsh structure and function (Butzeck et al., 2015; Pennings & Bertness, 2001). Soil salinity levels vary among marshes and across a marsh's surface depending on several factors. These include local sea salinity, distance from open ocean, level of freshwater influence, tidal flushing, soil type, evapotranspiration rates and precipitation (Odum, 1988; Wang et al., 2007). Many of these factors are also seasonally driven.

Salinity influences vegetation communities, competitive dynamics and productivity in salt marshes (Cooper, 1982; Pennings et al., 2005). Salinity changes may also impact marsh functions or trigger conversion to other habitat types. Previous research has also suggested that marshes at the lower and upper salinity ranges may be disproportionately affected by sea-level rise (Craft et al., 2009). Monitoring salinity will signal marsh persistence and changes to ecological functioning. This may be particularly important because climate change is impacting factors controlling marsh salinity, including sea surface salinity (Gulev et al., 2021; Statistics Canada, 2021).

Salinity measurements can be taken in situ or can be modelled. Marsh salinity models may be created in the future using some of the factors suggested at the beginning of this section. However, a lack of research on the topic, and the complexity of processes underlying salinities make this presently unfeasible. Future advances in modelling using SAR data may also prove promising for measuring soil salinities in salt marshes (Taghadosi et al., 2019). At this time, sea surface salinity changes and select related climate variables will be used as a proxy for salinity change within salt marshes.

Proposed metrics:

- Seawater salinity adjacent to marsh
- Average soil salinity in each zone
- Precipitation changes

2.2.2.2 Pollution

Several pollutants—substances that have a harmful effect on the environment—are known to negatively impact salt marshes. These include, for example, nutrients transported into salt marshes in freshwater runoff from built-up areas and agricultural environments (Cole, Kroeger, McClelland, & Valiela, 2006; McClelland & Valiela, 1998b), oil from oil spills, and heavy metals from sedimentation (DeLaune et al., 1981) and precipitation (Watmough et al., 2017). Salt marsh soils have the capacity to capture and hold pollution including some nutrients and metals, performing important water filtration functions (Reddy et al., 2000; Valiela et al., 1997); however, increased pollutant inputs can have negative impacts on salt marsh condition.

Nutrient pollution alters the vegetation community (Levine et al., 1998) and vegetation growth (Langley et al., 2013) in salt marshes because plant growth is typically limited by nitrogen and phosphorus availability (Broome et al., 1983; Kiehl et al., 1997). Nutrient-enriched marshes may also be vulnerable to invasion by exotic species (Gedan et al., 2009) and have decreased root production leading to soil erosion (Turner, 2011). Salt marsh vegetation can also be indirectly and negatively impacted in areas where marine waters are nutrient-enriched or where algal blooms are occurring (Newton & Thornber, 2012; Wasson et al., 2017).

Besides nutrient pollution, oil spills can cause long-lasting decreases in vegetation cover, causing cascading impacts in the ecosystem (Mendelssohn et al., 2012). The presence of heavy metals has a lower direct impact because salt marsh vegetation is tolerant to metal toxicity (Nikalje & Suprasanna, 2018). However, as the link between terrestrial watersheds and the marine environment, salt marshes can release metal pollution (Gedan et al., 2009; Weis & Weis, 2004) and nutrients (Page et al., 1995) into the marine food web. This process has impacts on other coastal and marine habitats and on provisioning ecosystem services (McClelland & Valiela, 1998a; Valiela et al., 2000). Quantifying pollution is important for understanding marsh condition and impacts on ecosystem services and also is also relevant for policy and decision making.

Since pollution is human derived, it can feasibly be measured by tracking inputs of harmful substances into the environment. Thus, measurement of this condition variable will draw on Canada's National Pollutant Release Inventory, a database of mandatory reports from select facility types tracking the release of many environmental pollutants, and the National Aerial Surveillance Program, which monitors marine pollution spills. The list of pollutants that will be monitored is based on the literature and expert opinion and will be updated as needed. Land use and ecosystem condition in areas surrounding salt marsh may be included in this variable since they can affect pollution inputs (e.g., presence and density of a vegetated buffer, adjacent industry releasing pollutants). These issues are further discussed in section 2.2.6.2.

Proposed metrics:

- Pollutant load per unit area from runoff and from marine sources by pollutant type
- Cumulative number of pollution events by pollutant type over a time period (e.g., last year or last ten years), including both marine and terrestrial pollution
- Algal bloom or eutrophication metrics within a unit of distance
- Quantifying surrounding land uses when direct measurements cannot be made (section 2.2.6.2)

2.2.3 Compositional state

Compositional state variables describe the communities of the biotic (living) components of an ecosystem (United Nations et al., 2021). Vegetation communities and animal biodiversity are the important components of salt marshes that fall under this category.

2.2.3.1 Vegetation community (dominant and invasive species, zonation)

Salt marsh vegetation plays an important role in the delivery of many ecosystem services (Ngulube, 2021; Rabinowitz, 2020), supports biodiversity (Ziegler et al., 2021), and is linked to the persistence of the marsh over time (Cahoon et al., 2020; Feagin et al., 2009). Vegetation communities are collections of plant species that live together in a specific place. In a salt marsh, vegetation communities form zoned patterns parallel to the ocean where each zone is dominated by one or two species, with other species intermixed in low abundances (Pratolongo et al., 2019; Vince & Snow, 1984). This zonation occurs due to plant species' salinity and flooding tolerance, and their relative ability to compete for resources (Crain, Silliman, Bertness, & Bertness, 2004; Pennings et al., 2005). This distinct zonation pattern is characteristic of mature, healthy salt marshes.

In Canada, salt marshes occur on every coast and display high variability in native vegetation species (MacKenzie & Moran, 2004; Martini et al., 2019; Pratolongo et al., 2019). This variability in native vegetation is related to underlying differences in abiotic conditions (Crain et al., 2004; Porter et al., 2015). As a result of this relationship, vegetation communities may shift in response to climate change (Colombano et al., 2021).

Despite outward differences in vegetation communities, ecological classifications typically group salt marshes together as a single ecosystem type (e.g., Keith et al., 2020). There is little research exploring whether ecosystem function and ecosystem service supply differs among salt marshes with varying vegetation communities. Some studies have suggested that local vegetation species and community structures influence wave attenuation capacity (Schulze et al., 2019; Vuik et al., 2018) and use by fish (Ziegler et al., 2021). Moving forward, more information on these differences is needed to interpret the impact of vegetation community on ecosystem condition and related ecosystem service changes.

Ideally, data for this variable would come from a national level survey of salt marsh vegetation (e.g., as done in the United States, (United States Geological Survey National Wetlands Research Center, n.d.; United States National Parks Service, n.d.)); however, this would be a massive undertaking. As a proxy, multispectral (Silvestri & Marani, 2004; Sun et al., 2018) or SAR satellite imagery analysis (van Beijma et al., 2014) may allow zonation pattern identification for use as a vegetation community proxy (Zhao et al., 2019). A practical drawback to the use of remote sensing is that changes in zonation patterns may not always capture changes in salt marsh species (e.g., if one zone is entirely replaced by an invasive species, the number of zones remains the same). A long-term decrease in the number of vegetation zones or distribution of area among zones, however, may indicate changes to or loss of salt marsh. Additionally, data specifically on rare or endangered species in salt marshes may be available from Conservation Data Centres.

While native plant species are critical to marsh function, invasive plant species can outcompete native species and in extreme cases completely overrun the marsh (Gallardo et al., 2015; Minchinton et al., 2006). This decreases ecosystem condition and ecosystem service supply (Grout et al., 1997; Warren et al., 2001). Degraded marshes may be vulnerable to invasion. For example, the non-native grass phragmites (Phragmites australis ssp. australis) can take over in nutrient-enriched and disturbed marshes (Bertness et al., 2002; Ravit et al., 2007). There is a considerable body of research on the negative impacts of phragmites in coastal marshes in North America (e.g., Meyerson et al., 2009; Weinstein & Balletto, 1999), but less research on other species that may invade salt marshes in response to changing conditions.

Several other invasive aquatic and wetland vegetation species in Canada have the potential to displace native salt marsh vegetation. These include purple loosestrife (Lythrum salicaria), an aggressive wetland invader tolerant to brackish water that can be found widely across Canada (Invasive Species Centre, n.d.; Konisky & Burdick, 2005) and yellow flag iris (Iris pseudacorus), which can invade salt marsh (Gerwing et al., 2021; Sutherland & Walton, 1990). On the West Coast, several aggressive Sporobolus spp. grasses (formerly Spartina spp.) introduced from the East Coast (Harney, 2008; Saarela, 2012), as well as narrow-leaved cattail (Typha angustifolia) and blue cattail (Typha x glauca) (Stewart, 2021) are negatively impacting salt marshes. According to the Conservation of Arctic Flora and Fauna, there are few invasive species currently in the Arctic, but more are expected to arrive with climate change (Conservation of Arctic Flora and Fauna, 2013).

To present data on invasive species, it is possible to compile a database of invasive species occurrence records from internationally available datasets such as the Global Biodiversity Information Facility (GBIF)—a collection of records from many sources including herbaria and citizen science from the early 1900s to present. There are several limitations to using these data including that they provide biased spatial and temporal coverage. There can also be issues with citizen science identifications which may be biased against less charismatic plant species. More research is required to use this data effectively in salt marsh accounts.

Proposed metrics:

- Marsh vegetation community change over time, for example, measured by a diversity index (e.g., Shannon index) and/or species richness
- Zonation pattern presence/absence
- Number of distinct zones
- Area in each zone
- Number of invasive species individual occurrences within a spatial unit (e.g., within marsh boundaries, within a surrounding buffer zone, within an estuary)
- Number of invasive species within spatial unit

2.2.3.2 Animal biodiversity (native and invasive species)

As in any ecosystem, animals play important functional roles in salt marshes and can be an indicator of ecosystem condition (e.g., Silliman & Bertness, 2002; Vivian-Smith & Stiles, 1994). Salt marshes are used by a wide range of species; however, since marshes alternate between periods of flooded and dry conditions, occupation of these spaces by wildlife is often transient. Fish and crustaceans may occupy the marsh surface at high tide but swim out with the receding tide (Ziegler et al., 2021). Smaller crustaceans and fish can also take refuge in wet mud or pannes during low tide and can play a role in modifying salt marsh soils (Able et al., 2012; Pennings & Bertness, 2001). Terrestrial animals use the marsh during low tide, for example, birds feed on invertebrates in the soils or directly on plants (Pennings & Bertness, 2001; Roberts & Robertson, 1986), birds nest in the high marsh and pollinators have been seen visiting salt marshes though further research is required to understand how pollinators use this ecosystem (Roulston, 2021) (also see section 2.3.3.3 on pollination).

In contrast, invasive animals can negatively impact salt marshes. For example, the marsh snail (*Littoraria irrorata*) grazes on marsh plants on the southern Atlantic Coast of the United States (Bertness et al., 2004) and the European green crab (*Carcinus maenas*) causes marsh erosion and loss in Maine (Aman & Wilson Grimes, 2016). There is, however, little to no research on this topic in Canada. Gaining an understanding of the animal biodiversity in marshes over time will help to understand marsh condition.

Biodiversity indices have been created for coastal and marine ecosystems using global datasets such as IUCN and GBIF (e.g., Eddy et al., 2021; Sievers et al., 2021); however, their creation requires an immense amount of data and resources, limiting repeatability. Presently, ways to measure this variable on a national scale are being explored.

Ideally, selected metrics will reflect the abundance and species richness of select native and invasive salt marsh species. Their development will likely involve a literature review to create a comprehensive list of salt marsh species, from which to identify focal species including: indicator species, keystone species, cultural keystone species, economically important species, endemic species, at risk species, and specialist species. Data development will rely on datasets from global sources (e.g., IUCN), provincial and territorial governments, federal government (e.g., Fisheries and Oceans Canada, Environment and Climate Change Canada, and Parks Canada), universities, and non-governmental organizations (e.g., Conservation Data Centres).

Data may also be drawn from citizen science databases such as eBird and GBIF, although these data require additional assessment and treatment to avoid biases inherent in them. A proxy for biodiversity associated with salt marsh is under development which will integrate survey, citizen science, and range data. The use of alternative approaches such as emerging eDNA (environmental DNA) technology (Thomsen & Willerslev, 2015; University of New Hampshire, National Estuarine Research Reserve System, n.d.) would require further research and establishment of monitoring programs.

Proposed metrics:

- Biodiversity index for animal species that use salt marsh and have a known range within a specified distance from a salt marsh, incorporating information on importance of salt marsh habitat, conservation status, and importance of that species (e.g., keystone species)
- Number of keystone, indicator, rare/endangered or otherwise important species individual occurrences within a spatial unit (e.g., within marsh boundaries, within a surrounding buffer zone, within an estuary)
- Number of invasive species individual occurrences within a spatial unit (e.g., within marsh boundaries, within a surrounding buffer zone, within an estuary)
- Number of invasive species within spatial unit

2.2.4 Structural state

Structural state variables capture properties of the ecosystem as a whole, or its major biotic components (United Nations et al., 2021). In salt marshes, the structural state of the vegetation is the most important variable.

2.2.4.1 Vegetation structure (stem density, biomass)

Salt marsh vegetation forms zoned patterns where each zone is dominated by one or two salt- and flooding-tolerant species. These plants grow densely and are highly productive (Serrano, Kelleway, Lovelock, & Lavery, 2019). The vegetation's physical structure (e.g., stem density and biomass) supports ecosystem functioning (e.g., Cahoon et al., 2020; Kearney & Fagherazzi, 2016) and ecosystem service supply.

The physical structure of salt marsh vegetation is linked to wave attenuation (Möller et al., 2014), shoreline protection (Shepard et al., 2011), and marsh use by fish (Whitfield, 2017; Ziegler et al., 2021). Vegetation structure also plays a role in carbon sequestration (Serrano et al., 2019; Tobias & Neubauer, 2019) and accretion (Gleason et al., 1979; Mudd et al., 2010) as organic carbon (trapped through photosynthesis in plant matter) and inorganic carbon (sediment trapped on plant stems) are incorporated into marsh soils over time. Dead plant matter is also washed into nearshore environments with falling tides, providing nutrients for species that are prey for commercially important fish (Jänes et al., 2020; Valiela et al., 2000). Changes in the salt marsh vegetation structure resulting from climate change or other external pressures would impact these processes, potentially causing loss of extent or ecosystem service supply.

Vegetation indices (VIs) such as normalized difference vegetation index (NDVI, which indicates the 'greenness' of an area in imagery) are commonly used to identify vegetated areas and measure characteristics such as biomass and stem density (Eastwood et al., 1997; Xue & Su, 2017). They are simple to calculate using widely available satellite or other aerial imagery (e.g., Ghosh et al., 2016). However, tidal flooding, standing shallow water, and bare ground in salt marsh, as well as spatial and temporal variations in these characteristics, can affect calculations (Kearney et al., 2009; Xue & Su, 2017). Authors have had success using NDVI to measure vegetation structure in salt marsh (Hardisky et al., 1984; Lopes et al., 2020), but alternative VIs that are less sensitive to water and soil reflectance are also used. These include the modified soil adjusted vegetation index, global environmental monitoring index (Eastwood et al., 1997), wide dynamic range vegetation index (Ghosh et al., 2016; Gitelson, 2004) among others (Miller et al., 2019). Some of these are not possible to capture with all types of remote sensing imagery.

Other options for measuring or modelling aboveground biomass or vegetation heights in salt marshes include using DEMs and digital surface models (DSM; a model of the Earth's surface that reflects vegetation, buildings, etc.), where an early season DEM can be subtracted from a DSM taken at peak biomass to obtain vegetation height. In addition, SAR has been used in coastal wetlands to estimate aboveground biomass relatively successfully (Jensen et al., 2019).

In salt marshes specifically, obtaining data at an adequate spatial resolution to capture marsh size, shape and vegetation zonation patterns is an additional complication. Biomass production and vegetation characteristics, for example, can vary among vegetation species (Miller et al., 2019; Mo et al., 2018), within a species, and across the marsh surface (Kirwan et al., 2009; Tobias & Neubauer, 2019). Previous research has suggested that measuring vegetation structural characteristics using satellite imagery without accounting for vegetation zonation patterns can be effective at a broad scale (Ghosh et al., 2016). An additional consideration is that VIs can reach a saturation point in high-density vegetation (Gitelson, 2004), such as that in a salt marsh. Using one or more VIs, however, is likely to give a reasonable indication of salt marsh vegetation structure. Presently, Google Earth Engine is being used to calculate and compare several VIs from Sentinel-2 imagery to report on this condition variable. Over time, more accurate measures of vegetation structure such as biomass may be produced through modelling efforts or the use of multi-instrument techniques (e.g., Lumbierres et al., 2017; Mo et al., 2018). In addition, initial accounts will also include climate variables that affect plant productivity, such as temperature and precipitation (Charles & Dukes, 2009; Kirwan et al., 2009).

Proposed metrics:

- Total area within specified VI ranges over a period of time
- Proportion or total marsh area with VI change outside a specified normal range over a period of time
- Number of marshes with average VI change outside a specified normal range over a period of time
- Growing degree days
- Vegetation height

2.2.5 Functional state

Functional state variables describe the interactions between different components of an ecosystem (United Nations et al., 2021). For salt marshes, this includes describing disturbance events.

2.2.5.1 Disturbance events (wrack, ice, herbivory)

Natural disturbances are an integral part of salt marsh development and persistence over time. Specifically, disturbances by wrack (mats of plant debris), herbivory (grazing by animals), and ice (formed on the marsh or in the ocean) are common in salt marshes. Wrack and ice play an important role in accretion (Argow et al., 2011; Dionne, 1993) and vegetation dynamics (Ewanchuk & Bertness, 2003; Rabinowitz et al., 2022), and shape salt marsh topography (Dionne, 1969). Ice build-up can also protect the marine edge of salt marshes from erosion caused by waves. The magnitude, duration, and nature of ice and wrack disturbances are liable to change with climate change because they are seasonal processes. For these reasons, tracking them in condition accounts is relevant.

Salt marshes are also subject to herbivory, particularly from geese. There is evidence of goose herbivory drastically altering salt marshes along Hudson Bay and the West Coast of Canada because of changes in goose behaviour and population size over time (Dawe et al., 2015; Jefferies et al., 2006). Herbivory pressure is likely to change in response to climate change and the ongoing introduction of non-native species, potentially causing impacts on salt marsh condition.

National-scale data exist for sea ice cover, but little to no data exist on other pressures described here. Climate data such as temperature and length of the ice season will provide supplementary information on icing events with the potential to cause disturbance in salt marshes. Methods for tracking wrack and herbivory, however, have not yet been addressed. Remote sensing may be used in the future to gather information on these types of disturbances in salt marsh (e.g., Jefferies et al., 2006), but this variable will be the subject of more research as accounts are developed, particularly on the relationship between the presence of disturbing agents and actual impacts caused.

Proposed metrics:

- Area impacted by disturbance, by type of disturbance
- Number of events per year, by type of disturbance
- Number of days below 0° C
- Goose population numbers or other herbivore population numbers

2.2.6 Landscape and seascape

Landscape and seascape variables provide details about ecosystems at a coarse spatial scale and can incorporate information about the surrounding lands. This section covers tidal barriers and restrictions, surrounding land uses, and the configuration of salt marshes on a landscape scale.

2.2.6.1 Tidal barriers and restrictions

Humans have a long history of constructing hard coastal infrastructure, such as seawalls, to protect coastal settlements and combat coastal erosion; however, coastal infrastructure can be damaging to adjacent environments. Coastal infrastructure may be built at any distance from the marine edge, depending on its purpose (e.g., causeways or dykes at the terrestrial edge and seawalls or revetments at the marine edge). It can also be built in the water (e.g., breakwaters designed to protect from waves). These constructions can cause salt marsh loss if built on top of a marsh or if they restrict or prevent tidal flooding (e.g., in the case of dykes or improperly sized culverts) thereby partially or fully converting marsh into terrestrial or freshwater habitat (Heery et al., 2017; Smith & Warren, 2012). The conversion of salt marsh to terrestrial land, which may subsequently be used for other purposes such as agriculture, is a major cause of tidal wetland loss in Canada (Bowron et al., 2012; Gedan et al., 2009). Additionally, infrastructure (e.g., roads, coastal development) can block landward migration of salt marsh (i.e., limit natural adaptability to sea-level rise—termed coastal squeeze (Doody, 2004)), eliminate transitional habitat at the terrestrial edge and marine edge of a marsh, and contribute to habitat fragmentation at the landscape scale (Dugan et al., 2011; Leo et al., 2019).

Infrastructure along the coast is also known to impact the condition of nearby salt marshes. Coastal infrastructure affects natural coastal erosional and sedimentary processes, as well as hydrology at the local and landscape scales. This can cause salt marsh degradation and loss (Bozek & Burdick, 2005; Dugan et al., 2011). Coastal construction can also introduce invasive species to salt marshes (Currin, 2019).

These effects all contribute to well-documented changes in animal behaviour (Klein et al., 2011; Peterson & Lowe, 2009) and decreases in coastal and nearshore biodiversity, having a negative effect on salt marsh plants and animals (Partyka & Peterson, 2008; Peterson et al., 2000). These impacts on salt marsh extent and condition, and the direct links to policy and decision-making make this a valuable condition variable to include in salt marsh accounts.

At this time, existing datasets that include the locations of coastal infrastructure are being gathered. Moving forward, an assessment of tidal restrictions (location and level of restriction) and a register of new constructions affecting coastal wetlands, along with details on the area affected by existing and new barriers would be useful to integrate into this work. Since coastal infrastructure can affect salt marsh at the landscape scale, appropriate spatial boundaries by which to measure this variable are needed. In addition, future consideration may be given to ‘green’ or ‘hybrid’ coastal infrastructure that harnesses natural ecosystems (e.g., built salt marshes) or that combines ecological elements with traditional hard elements to provide coastal protection (Currin, 2019; Sutton-Grier et al., 2015).

Proposed metrics:

- Number of tidal barriers and their level of tidal restriction (full or partial) within a spatial unit
- Number or length and type of coastal infrastructure within a buffer zone around marsh or a larger spatial unit
- Area of impacted salt marsh behind tidal barrier or restriction
- Quantifying surrounding land uses when direct measurements cannot be made (section 2.2.6.2)

2.2.6.2 Surrounding land uses

Land uses surrounding salt marshes are connected to several pressures on marsh condition. Tidal barriers and coastal infrastructure, as discussed in section 2.2.6.1, present barriers to the natural landward migration of salt marshes as an adaptation to sea-level rise, can cause excessive erosion, influence coastal dynamics, and limit habitat connectivity (Dugan et al., 2011; Peterson & Lowe, 2009).

Built-up areas and agricultural land uses are associated with pollution and invasion by exotic species (King et al., 2007; Silliman & Bertness, 2004), as discussed in sections 2.2.2.2 and 2.2.3.1. They can also contribute to the loss of salt marshes that become sandwiched between rising seas and built-up areas (Leo et al., 2019). Surrounding built-up areas and agricultural land uses can also impact salt marsh vegetation, salinity, hydroperiod, and water table (Álvarez-Rogel et al., 2007) and are associated with decreased animal diversity and abundance (King et al., 2005; Morley et al., 2012). For these reasons, salt marshes that are surrounded by human-modified landscapes are more likely to be in poor condition with modified ecosystem service supply.

The first iteration of this variable will be measured using existing national and/or global land use and land cover datasets (e.g., Agriculture and Agri-Foods Canada, 2018; Statistics Canada, 2021). Simple calculations of the area in various land cover categories (e.g., natural, built-up areas, agriculture, mixed) within a specified distance from salt marsh boundaries will be calculated for this variable.

Proposed metrics:

- Area or proportion of land uses within a spatial unit (e.g., within marsh boundaries, within a surrounding buffer zone, within an estuary), by type
- Length of average number of roads within a spatial unit, by classification (e.g., highway, local road, etc.)
- Distance to nearest infrastructure
- Population density within a spatial buffer zone

2.2.6.3 Landscape configuration

Landscape configuration can be taken as the spatial configuration of marsh patches at the local and landscape scales. This configuration can influence marsh condition and ecosystem service supply. Marsh shape, size, length of marine edge, and relative location of marsh along the coast are all part of the landscape configuration and can impact marsh functioning (e.g., French, 2019; Wu, 2019). Marine edge is a particularly important habitat as it is the connection between marsh and the marine environment (Minello et al., 1994; Ziegler et al., 2021). In addition, marshes in closer proximity to other intact marine habitats, including other marshes, have been shown to contain higher animal biodiversity (Litvin et al., 2018; Partyka & Peterson, 2008). Landscape configuration is also associated with a salt marsh's sea-level rise adaptation capacity (Wu, 2019).

Measurement of landscape configuration can be performed using relatively simple spatial calculations in geographic information systems (GIS) software based on extent data. One major complication with this approach is that current extent datasets do not accurately reflect tidal channels (edge habitat) within salt marsh—this will require consideration before completing these analyses. Additional measures of landscape configuration may also be produced in the future using software such as Fragstats (McGarigal & Marks, 1995), which analyzes aerial imagery for spatial patterns.

Proposed metrics:

- Average marsh size within a spatial unit
- Average distance to nearest marsh within a spatial unit
- Area to edge ratio
- Connectivity metric (e.g., Connectance Index in Fragstats)

2.2.7 Reference condition

The SEEA–EA recommends establishing a reference condition for ecosystems as a comparison point to determine relative condition over time (United Nations et al., 2021). This reference condition should exemplify an 'ideal' or 'healthy' state. Typically, reference conditions are selected based on the conditions from a historical point in time or from an area that is largely unmodified by humans. This selection can be difficult for salt marshes for multiple reasons.

In Eastern Canada, salt marshes were some of the first lands modified by colonial settlers. Since then, salt marshes have been ditched, drained, grazed by livestock, and otherwise destroyed across North America (Bertness et al., 2004). In some cases, these modifications are maintained, and in others they have been abandoned. Salt marshes may re-develop in areas where modifications have been abandoned, but functions may be altered due to past modifications. This makes identifying un-modified reference marshes or marshes that have been un-modified long enough that they have returned to a 'natural' state difficult, particularly when data from salt marshes in general are lacking.

Data from salt marshes are less available for remote areas of Canada including the Arctic, where there is likely considerable salt marsh extent beyond what is currently mapped. This geographical bias complicates the identification of reference conditions or reference marshes across the country, especially considering the inherent variation in characteristics, for example, salinity, across the country. Additional variation in marsh characteristics on smaller spatial scales (within a marsh, within an estuary) make it even more difficult to adopt reference values that reflect these nuances.

At this time, data from salt marshes that have been protected for at least a decade will be used to determine reference conditions, with a focus on historically un-modified marshes where possible. Canada has a spatially-explicit database of protected salt marshes that is relatively large and includes areas of protected marsh in most regions of the country, which will enable geographically-explicit comparisons of salt marsh condition. These marshes will provide the closest possible measure of ‘natural’ salt marsh condition. A limitation of this approach is that climate change is already impacting salt marshes. As extent data improves, it is possible that a new approach for measuring reference condition will be needed in areas where data are currently lacking.

2.3 Ecosystem services

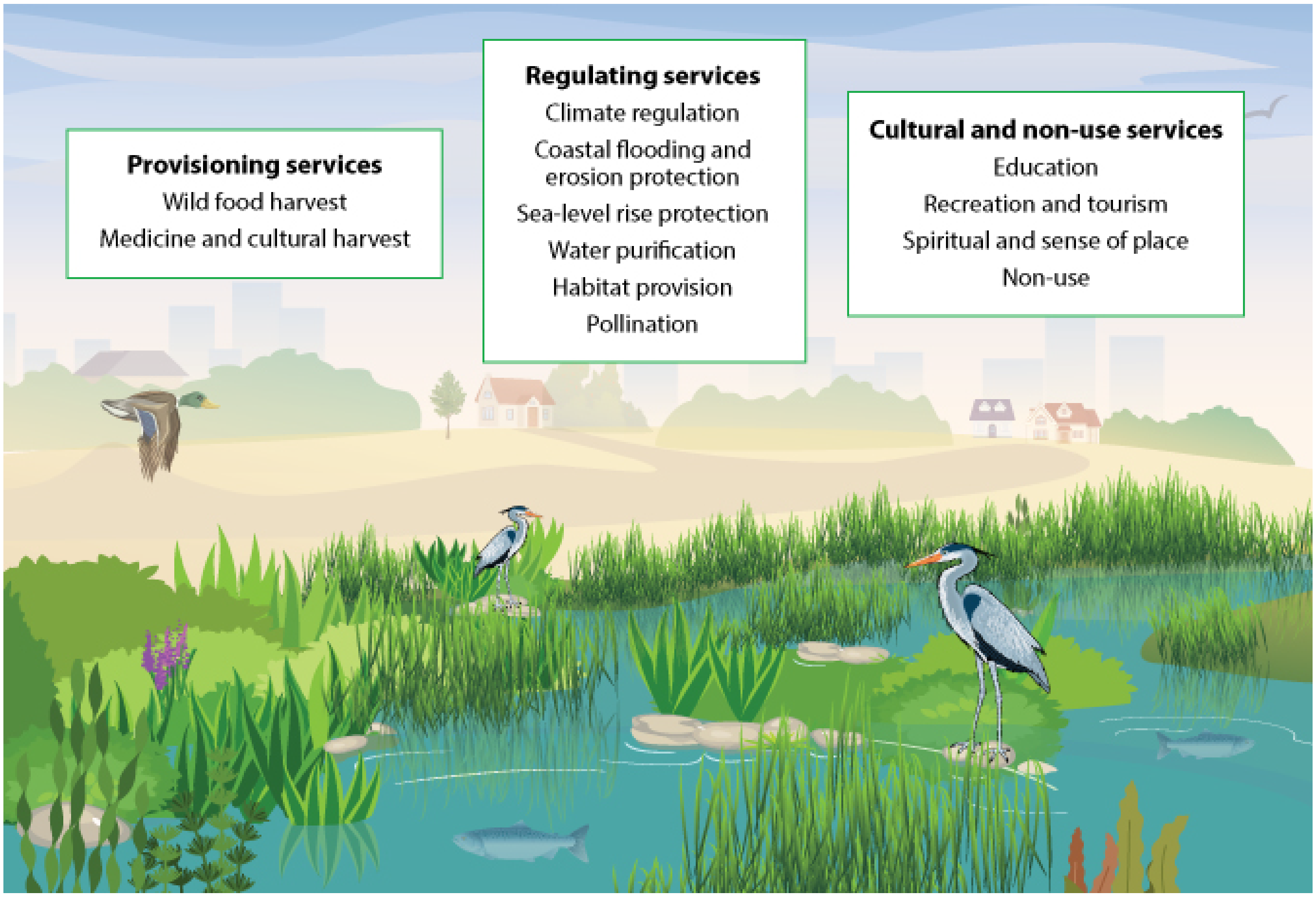
Ecosystem services are broadly defined as the ecosystem contributions to the benefits that humans gain from the natural environment. Accounting for ecosystem services is a key part of the SEEA–EA framework (United Nations et al., 2021) as this process links the extent and condition of ecosystems with their capacity to provide services on which humans rely. Ecosystems with healthier condition provide more services than ecosystems which are in poor condition or degraded.

The SEEA–EA framework categorizes ecosystem services into three main groups: provisioning, regulating and maintenance, and cultural (United Nations et al., 2021). Services are provided by ecosystems and have a beneficiary. Beneficiaries can be a local or global population or another ecosystem. Services are final services if humans benefit from them, and intermediate or supporting if another ecosystem or species benefits from them.

Ecosystem services provided by salt marshes are presented in the following sections, with a description and potential data sources and methods. Logic chains describing the inputs, beneficiary and use of each service are presented in Table 3. Several of these services are difficult to measure directly and in these cases the use of proxies is discussed. Measurement of some services requires methodological development or data that are not currently available—data gaps will therefore remain in the initial accounts.

Services can be measured in both physical (e.g., fishery landings in tonnes) and monetary terms (e.g., fishery landings measured by dollar sale value) (United Nations et al., 2021). Monetary values are used to link to policy decisions and the system of national accounts. This paper, however, concentrates on physical measurements of services, using monetary methods only where data on physical flows is unobtainable. Monetary valuations of services will be developed at a later stage, bearing in mind that these will change not only due to ecosystem change but also due to variability in the economy.

Figure 2
Salt marsh ecosystem services



2.3.1 Provisioning (wild harvest, raw materials)

Provisioning services result from extracting or harvesting biomass from ecosystems. They are the most obvious way that humans benefit from ecosystems around them. The harvest of food, raw materials, medicinal ingredients, and cultural or decorative items fall under the category of provisioning services and they can be measured by the physical amount of material extracted (including all wastage).

Several food species, both plant and animal, are harvested from salt marshes across Canada. Glasswort (*Salicornia* spp.), known by many common names including pickle weed, sea asparagus, samphire greens and “titanes de souris,” is harvested from salt marshes around the world. It is occasionally found in grocery stores, community markets, specialty online food stores and restaurants when in season (Clapson, 2014). Seaside plantain (*Plantago maritima*), orache (*Atriplex* spp.) and sow thistle (*Sonchus* spp.) are also harvested from salt marshes for food in Canada (Cohen, 2018). Additionally, Springbank clover (*Trifolium wormskioldii*) and Pacific silverweed (*Potentilla egedii*) were traditionally harvested as root vegetables from salt marsh by First Nations including the Nuu-chah-nulth and Kwakwaka’wakw. These First Nations were known to manage salt marshes to increase production of these plants (Turner et al., 2013).

Recreational fishing, clam digging, and waterfowl and game bird hunting also frequently take place in salt marshes (Environment and Climate Change Canada, 2020; Environment and Climate Change Canada, 2021). Historically, the Mi'kmaq First Nation collected shellfish in salt marshes, as shown by piles of periwinkle and other shellfish remains (Nova Scotia Museum, 2020).

Salt marsh plants are also harvested for purposes other than food, including for medicinal, cultural and decorative purposes. Sweetgrass (*Anthoxanthum* spp.), an extremely important plant in many Indigenous cultures across Canada, grows in salt marshes across the country (Tiner, 2009). Mi'kmaq people harvest sweetgrass from salt marshes on the East Coast for medicinal purposes, along with sea lavender (*Limonium carolinianum*) and cattails (*Typha* spp.) (Sherren et al., 2021). Cattail leaves and stems are used to make a number of items, from baskets and bags to paper and cloth while sea lavender is also known to be harvested for floral arrangements (Baltzer et al., 2002).

It is difficult to track the total harvest of food and materials, as these harvesting activities are frequently subsistence based and have limited commercial sales. As a specialty item, prices for glasswort ranged from $12 to $20 per pound in 2015 (Langford, 2015), with similar prices at online shops in 2022. Data on Canadian grocery store sales of glasswort are collected, though the values are currently unpublishable due to confidentiality requirements. Other foods harvested from salt marsh are rarely sold through grocery stores, making collection of sales data difficult. Current surveys undertaken on recreational fishing are unable to provide the required data as the detailed location of catch is not collected, making it difficult to attribute these data to a particular ecosystem. Harvests for medicinal and cultural purposes are also very difficult to measure.

In the future it may be possible to measure wild provisioning from salt marshes and other ecosystems using crowdsourcing, surveys of foraging habits, and Indigenous engagement. For both foraging and fishing, collecting social media images that were labelled and geotagged could indicate which salt marshes are used for provisioning. There are, however, inherent risks to using crowdsourced and social media data due to participation bias.

Proposed metrics:

- Harvested biomass
- Sales of harvested plants or animals
- Crowdsourcing or surveying to establish provisioning harvested biomass
- Counts of geotagged social media posts involving harvesting in salt marshes

2.3.2 Regulating

Regulating and maintenance services result from an ecosystem's ability to influence and regulate biological processes, climate, and hydrological and biochemical cycles to maintain environmental condition (United Nations et al., 2021). These services are plentifully supplied by salt marshes, benefitting local and global beneficiaries. This group of services includes services such as climate regulation, coastal flood protection, and erosion control.

2.3.2.1 Climate regulation

The role of salt marshes in global climate regulation through carbon storage and sequestration has only been valued relatively recently. The dense root structure and slow decomposition rates in salt marshes make them ideal for long-term carbon storage (Connor et al., 2001). Based on global average carbon sequestration rates (McLeod et al., 2011) known Canadian salt marsh ecosystems may sequester as much as 785 kilotonnes of carbon per year.

Carbon storage and sequestration (the process by which carbon is captured) capacity vary considerably among marshes given the plant community variability within and among salt marshes (see section 2.2.3.1). As such, carbon storage and sequestration in accounts will be presented using regional estimates where possible (e.g., Clayoquot Sound (Chastain, 2017), Boundary Bay (Gailis et al., 2021), Bay of Fundy (Connor et al., 2001)). As the accounts develop, ecosystem service modelling platforms and more sophisticated modelling techniques using national data will be used to build on these simple regional estimates.

Salt marshes also provide microclimate regulation services by affecting local weather patterns through evapotranspiration (United Nations et al., 2021). However, given that salt marshes are usually close to open ocean areas, it is expected they have a minor impact on local climate in comparison to the ocean. Salt marsh along brackish rivers and at the ends of fjords may play a more significant role in the microclimate, but this is an avenue for future research.

Proposed metrics:

- Measured or modelled carbon sequestration and storage rate multiplied by area

2.3.2.2 Coastal flooding protection

Coastal flooding resulting from storm surge is expected to be exacerbated with the increasing frequency and intensity of storms over this century (Lemmen et al., 2016). This poses a risk to coastal communities, infrastructure and economically valuable land within the coastal zone. Recent studies have found that coastal marshes could decrease flood depths by 15% and save the same proportion of flood damage costs, saving millions of dollars (Narayan et al., 2017; Rezaie et al., 2020).

Ideally coastal protection services would be measured by the reduction in the area of built-up or managed ecosystems impacted by flooding. A marsh's ability to attenuate waves, thereby reducing the energy and height of waves, gives a good indication of its capacity to reduce flooding. There are several studies on salt marsh's ability to attenuate waves and storm surge over the width of a marsh (Möller et al., 2014; Ngulube, 2021; Rezaie et al., 2020; Trégarot et al., 2021). However given the large differences in vegetation community and structure among salt marshes (sections 2.2.3.1 & 2.2.4.1), a wave attenuation value can not be assumed based solely on the width of a marsh.

Thus, rather than supplying only modeled results based on marsh width, measurement will focus on variables that impact salt marsh's ability to attenuate waves (service supply), as well as the demand for this service. Variables impacting wave attenuation include marsh shape, size, vegetation community and structure, topography and wind sheltered status (Möller et al., 2014; Ngulube, 2021; Rezaie et al., 2020; Trégarot et al., 2021; Willemsen et al., 2020). These variables may be combined to form an indicator of potential protective ability.

Marsh width is a known factor in the ability of the marsh to provide protective services (Möller et al., 2014), and it is logical that length of the marsh marine edge will also impact the amount of protection a marsh can provide. Wind sheltered marshes have a higher capacity to attenuate waves (Willemsen et al., 2020) thus data on average wind speed and direction during storm season will be included in measuring this service.

Within a marsh, different vegetation species have unique stem flexibility, causing varying levels of friction and varying capacity to slow waves (Barbier et al., 2013). High stem density provides wave attenuation, thus vegetative index values will be included as a reflection of the vegetation structure (Thornton et al., 2019) as described in section 2.2.4.1. Topography within the marsh will also affect the wave attenuation capacity, as marshes which are segmented by large channels and pannes enable surge to travel farther inland (Barbier et al., 2013). With high resolution DEMs the proportion of marshes with these low elevation features can be estimated (section 2.2.1.1); however, suitable DEMs may not be available for all areas of the salt marsh.

The level of demand for the protection service will be measured by assessing the land area and type, population, building count and amount of infrastructure within the potentially impacted area that could be impacted by maximum historic storm surge height. Environmental factors such as wind exposure, wave properties and storm seasonality and frequency could be used to modify the potentially impacted area.

Using measures of potential protection and demand for protection described here, an indicator for flood protection services can be created for use in the accounts. The coastal vulnerability indicator detailed in InVEST (Sharp et al., 2020) and Chaplin-Kramer et al., (2019) is an example of this type of indicator.

Proposed metrics:

- Supply: Indicator including length, width, wind exposure, VI, continuity of vegetation and topography of marsh.
- Demand: Human population, infrastructure and land type at elevations within maximum storm surge height with consideration for local climatic and hydrologic conditions

2.3.2.3 Coastal erosion protection

Salt marshes also improve coastal stabilization, which can decrease the rapid coastal erosion occurring across Canadian coasts as a result of climate change (National Research Council, 2007). Due to their dense plant structure, marshes accrete sediment to increase in height and width over time if not prevented from doing so by manmade structures (sections 2.2.1.1 & 2.2.6.1). In addition, plant roots stabilize the soil by physically binding it together and contributing organic matter that increases soil cohesion (Feagin et al., 2009; Van Eerdt, 1985). Salt marshes also reduce wave energy and thus erosive capacity (Möller et al., 2014). Estimating prevented erosion is very difficult without local data, thus a similar approach to measuring coastal flood protection will be taken. An indicator composed of a suite of variables will be created as a proxy. These variables include marsh marine edge length, width and functions of vegetation index (VI) values, which determine the supply of the service. Demand for the service (susceptibility of adjacent land to erosion) can be determined by measuring population, land use and amount of infrastructure in areas adjacent to salt marshes, as well as the substrate type and wind and wave exposure of this area.

Proposed metrics:

- Supply: Indicator of marine edge length, width, soil type and functions of VI
- Demand: Human population, infrastructure and land use within a specified distance of salt marsh

2.3.2.4 Sea-level rise protection

Salt marshes can provide protection against the impacts of sea-level rise, such as increased flooding and erosion as described in the previous two sections. If marshes can accrete sediment faster than the local rate of sea-level rise and increased tidal amplitude, they will protect land behind them from the impact of higher sea-levels and avoid the need for costly infrastructure projects or population migration. Even with slower accretion they will increase the time before adjacent land is flooded permanently. As described in section 2.2.1.1, DEMs allow for a rough estimation of marsh accretion rates. Where turbidity data exists, this will also give an indication of availability of sediment for accretion in salt marshes. The demand for this service can be measured using local projected end-of-century sea-level rise estimates combined with the population, infrastructure and land types at elevations lower than projected sea-level rise. Note that although salt marshes may also protect populations as they grow inland, this will be measured as extent change, rather than a protective service provided by the marsh.

Proposed metrics:

- Supply: Rate of change in marsh elevation in comparison to sea-level rise and availability of sediment in water.
- Demand: Human population, infrastructure and land type within area at risk from sea-level rise

2.3.3 Intermediate regulating

Intermediate, or supporting services, are those services for which the beneficiary is another ecosystem or species. These intermediate services lead to improved final services supply, and are critical to the maintenance of environmental health. Salt marshes provide many important intermediate services, supporting both terrestrial and marine ecosystems.

2.3.3.1 Water purification

Salt marshes can filter agricultural and built-up area runoff and prevent this runoff from reaching other ecosystems. Salt marshes filter excess nutrients in runoff (Valiela et al., 2000) and prevent eutrophication of nearshore areas (Nelson & Zavaleta, 2012), though the ability to provide this service may vary seasonally (Sousa et al., 2012). The ability to provide this service depends on factors including vegetation structure (Nelson & Zavaleta, 2012), length of exposure to elevated nutrient levels (Deegan et al., 2012) and marsh age (Sousa et al., 2008)

Salt marshes can also reduce sediment levels and turbidity in nearshore waters through their sediment capture functions (Endresz, 2020). Drawing on the pollution condition variable's data (section 2.2.2.2), marsh's potential exposure to pollutants will be determined and combined with other physical information including soil characteristics and VI to create a water filtration indicator. Seasonal aspects, age of marsh, and vegetation type will be more difficult to assess at a national level, and will not be included in a first account.

Proposed metrics:

- Demand: Metrics as explained in section 2.2.2.2
    - Pollutant load per unit area from runoff and from marine sources by pollutant type
    - Cumulative number of pollution events by pollutant type over a time period (e.g., last year or last ten years), including both marine and terrestrial pollution
    - Algal bloom or eutrophication metrics within a unit of distance
    - Quantifying surrounding land uses when direct measurements cannot be made (section 2.2.6.2)
- Supply: Indicator of soil type and depth and VI

2.3.3.2 Habitat provision

Salt marshes provide important habitat for many species, both terrestrial and marine. For some of these species a salt marsh is an essential habitat for part of their life cycle and cannot be replaced. Through providing habitat for these animals, salt marshes support biodiversity and environmental health, and support final services such as fishing, recreation, and sense of place.

Many small fish use the channels and pannes found in marshes as a nursery habitat. These include striped bass (*Morone saxatilis*), herring (*Clupea harengus*), American eel (*Anguilla rostrata*), gaspereau/alewife (*Alosa pseudoharengus*), mummichog (*Fundulus heteroclitus*) and possibly juvenile American lobster (*Homarus americanus*) (Able, et al., 2012; Sherren et al., 2021). As these species age, they can become prey to fished species, or become available to recreational and commercial fisheries themselves.

Though data on catches from recreational fishing are not available, it is possible to estimate the contribution to commercial fisheries from the portion of the lifecycle spent in a salt marsh. Ideally juvenile fish density data in different ecosystems (salt marsh, seagrass, un-vegetated coastline) could be used to infer the contribution of different ecosystems to the fishery following the work by Jänes et al. (2020). These data are not presently available, thus the idea of a residency index can be used instead (McCormick et al., 2021). An estimate of the contribution of salt marsh to the fishery can be created by attributing a percentage of the total weight of fish recruiting to the fishery equal to the percentage of available nursery habitat that is salt marsh, using the assumption that natural mortality rates are equal across all nursery habitats (Deegan et al., 2002). This idea of a residency index could also be expanded to the time spent as an adult in different ecosystems to give the entire life cycle impact of a particular ecosystem.

There are also certain butterflies and birds that rely on salt marshes such as the salt marsh copper butterfly (*Lycaena dospassosi*), Nelson's sharptailed sparrow (*Ammospiza nelsoni*), coastal plain swamp sparrow (*Melospiza georgiana subsp. nigrescens*), willets (*Tringa semipalmata*) and American black duck (*Anas rubripes*) (Benoit & Askins, 2002; Nature Conservancy Canada, n.d.; Yerkes, n.d.). This habitat provision can lead to various final services such as provisioning through hunting, cultural services of recreation and well-being in the surrounding area, and pest control. Geographically explicit population estimates for each of these species would be an ideal measure of habitat provision. However, as these do not exist for many of these species, this service will be measured using the same metrics as the animal biodiversity condition section (section 2.2.3.2).

Proposed metrics:

- Fishery nursery supply: Recruitment weight to commercial fisheries proportional to the nursery area that is salt marsh
- Metrics from section 2.2.3.2 on native animal biodiversity
    - Biodiversity index for animal species that use salt marsh and have a known range within a specified distance from a salt marsh, incorporating information on importance of salt marsh habitat, conservation status, and importance of that species (e.g., keystone species)
    - Number of keystone, indicator, rare/endangered or otherwise important species individual occurrences within a spatial unit (e.g., within marsh boundaries, within a surrounding buffer zone, within an estuary)

2.3.3.3 Pollination

Salt marshes have not traditionally been considered to supply pollination ecosystem services since many salt marsh plant species are wind pollinated (Sherren et al., 2021). However, new work suggests pollinators do use salt marshes (Roulston, 2021). Bumble bees (*Bombus* spp.) and leafcutter bees (Family: Megachilidae) have been found visiting salt marshes in the Bay of Fundy while insect pollinated plants were flowering. These pollinators were also seen visiting flowers of prairie cordgrass (*Sporobolus michauxianus*). The same study also found that leafcutter bees removed leaves from prairie cordgrass, probably for nest building. On the West Coast, there is additional evidence of opportunistic usage of salt marshes by bumble bees (*Bombus terricola*) (Pojar, 1973). Other insects that use salt marshes such as butterflies, flies and mosquitos may also provide some pollination services (Peach & Gries, 2016). These lines of evidence suggest that salt marshes may support pollinator communities and provide pollination services.

The proportion of wild pollination supply attributed to salt marsh will be measured as the proportion of natural and semi-natural area that is salt marsh within 2 km (a typical bee maximum flight distance) of pollination dependent crops. As pollinators will use closer areas more frequently, a decay function based on distance will be used. It may also be possible to create an indicator of pollinator ecosystem suitability, which could be used to adjust the estimated proportion of pollination supply from each ecosystem. Demand for pollination will be measured using the area of agricultural land growing pollination dependent crops (Chaplin-Kramer et al., 2019) across the country.

Proposed metrics:

- Supply: Proportion of natural and semi-natural ecosystem area that is salt marsh within a 2 km buffer of pollinator dependent crops (weighted with a decay function and potentially adjusted for pollinator suitability of surrounding ecosystems)
- Demand: Area of agricultural land growing pollinator dependent crops across the country

2.3.4 Cultural and non-use

Cultural services involve experiencing and appreciating ecosystems either directly or indirectly (United Nations et al., 2021). These include educational, recreational, cultural and non-use services. A visitor to a salt marsh may experience several cultural services at the same time. For example, they may read an educational sign, enjoy a recreational activity such as hiking or fishing and feel a sense of well-being from spending time in a healthy ecosystem.

2.3.4.1 Education

Salt marshes can provide educational services in several ways. Interpretative signs and guided tours in marsh areas allow visitors to learn about the ecosystem and native species. Researchers studying salt marshes are benefiting from educational services, as well as passing on those services through publications and lectures.

Although it is difficult to estimate the educational services provided by salt marshes, they can be estimated using a combination of factors. For example, an indicator based on the number of researchers who work on aspects of salt marshes, the number of research grants provided by government and other organizations, published scientific papers and student theses as well as the number of education programs and maintained walks centered on the ecosystem could be used in the accounts.

Proposed metrics:

- Indicator including count of salt marsh researchers, research grants, published papers and student theses and count of maintained salt marsh walks and education programs

2.3.4.2 Recreation and tourism

Recreation and tourism services are also provided by salt marshes when they are used for activities such as fishing or bird watching. These types of activities may best be estimated using visit statistics for areas where visits are monitored. For instance, visits to salt marshes in national parks can be estimated using park visits proportionate to area of salt marsh in the park. However, recreational and tourism services are more difficult to measure at salt marshes outside parks.

One option for measuring these services outside parks is to use data from citizen science sites such as GBIF, eBird and iNaturalist, where the public can post species observations. Instagram or other social media sites may also be useful (Chen et al., 2020). There are, however, difficulties in using these data types for statistical accounts. There are inherent biases in the data as not all users of a salt marsh will post details online. These data should be used with caution, particularly for statistics comparing different uses or users.

Aside from these options, potential recreational use can be measured using a decay function over the distance from a populated area and accessibility (e.g., presence of roads), following models used in two recent studies (Capriolo et al., 2020; Mitchell et al., 2021). Similarly, potential recreational uses for tourists will include the amount of accommodation in the marsh accessible area.

Proposed metrics:

- Park visitor numbers, area weighted for salt marsh
- Visit counts from citizen science sites
- Post counts from geotagged and labelled social media
- Potential to supply recreation services measured using road access and distance from populated areas
- Potential to supply tourism services measured using road access and distance from tourist accommodation

2.3.4.3 Spiritual and sense of place

Salt marshes may also provide spiritual and mental health services for Canadians through their existence and use. For instance, knowing that the coast close to your community is healthy and can protect you from harm provides this beneficial service. Additionally, walking in nature (e.g., forest bathing) has been shown to reduce stress (Hanson et al., 2017). In these cases, healthier marshes are likely to improve service supply. Thus, an accessibility indicator (section 2.3.4.2) combined with an indicator of overall marsh condition will provide an estimate of this service.

Spiritual services and sense of place services unique to Indigenous peoples are also provided by salt marshes. Salt marshes are an important ecosystem for Indigenous nations, including the Mi’kmaq in Atlantic Canada (Sherren et al., 2021) and several nations on the West Coast (Turner et al., 2013) as discussed in section 2.3.1. The cultural value of salt marshes to Indigenous nations is something that cannot be measured without Indigenous engagement.

By their very nature, these well-being services are extremely difficult to measure as they are intangible and often overlap with other types of services (e.g., provisioning services such as foraged foods). A further complication is that an ecosystem's value varies among individuals and population distinctions. Thus, age and ethnicity, as well as other social markers, may play a role in the level of service a particular ecosystem provides. To reflect this, whenever possible, the population demand component for the service will be disaggregated. The potential to supply spiritual and sense of place services will be measured in the same manner as the potential to supply recreational services (section 2.3.4.2) using the proximity of road access and populated areas.

Proposed metrics:

- Supply: Condition indicator with further metrics after consulting key user groups
- Potential to supply cultural services using road access and distance from populated areas as well as make up of local population

2.3.4.4 Non-use

Non-use services are provided by an ecosystem irrespective of whether they are used or intended to be used by people (United Nations et al., 2021). Two measures of non-use services are the protected or conserved status of salt marshes, and the protected status of species that use salt marshes (Vind, 2018). By giving protected status to marshes or associated species, an intrinsic value is assigned to its continued existence and health for future generations to enjoy.

Using maps of protected and conserved areas along with salt marsh extent (Environment and Climate Change Canada, 2022), the area of salt marsh that is conserved can be established. There are, however, some issues with this measure. First, the percentage is likely to be overly high as protected salt marshes are more likely to be mapped and therefore included in extent accounts. Secondly, protected areas are sometimes created opportunistically, in areas where there is little or no known human use, to meet pledged protected area targets. These areas would not fall under cultural services as they are not protected expressly because they are of specific intrinsic value.

To measure protected species use of salt marshes, range data for protected species for which salt marsh is a known habitat (see sections 2.2.3.2 & 2.3.3.2) will be combined with salt marsh extent data to create a tally of protected species ranges which overlap salt marshes. The *Species at Risk Act* (SARA) list of protected species will be used to determine protected status.

Proposed metrics:

- Percentage of salt marsh area protected or conserved
- Count of protected species using salt marsh habitat

2.3.5 Perceived disservices

Finally, a discussion of ecosystem services would not be complete without mentioning services that some may not see as benefits. These few disservices tend to be only perceived as negative at the local level but support the regional and global services discussed above.

First, as large areas of salt marshes are flooded regularly by tides and contain decomposing plant matter, oxygen levels in soils are low. This can lead to bacteria build up, particularly in marshes with low levels of tidal flushing, which can cause a sulfurous rotten-egg smell (Friess et al., 2021). This odor may be unpleasant to visitors or local residents. However, this is not commonly reported and this same process allows salt marshes to store carbon (section 2.3.2.1), ultimately reducing greenhouse gas concentrations in the atmosphere.

Second, small pockets of water in salt marshes may provide breeding habitat for mosquitos, which could be a nuisance for the local population (Friess, et al., 2021). Mosquitos, however, are an important part of the food chain as a food source for birds, fish and other insects. Mosquitos may also provide some pollination services, depending on the local floral community (Peach & Gries, 2016). Methods of mosquito control when applied to marshes (altering hydrology or spraying pesticides) could impact the entire insect community of the marsh and thus a number of ecosystem services (Rochlin et al., 2011).

As ecosystem disservices are not included in the SEEA–EA accounts, metrics for these two disservices are not proposed.

Table 3a
Ecosystem services logic chain

Service type	Service	Factors determining supply		Factors determining use
		Ecological	Societal	
Provisioning	Wild food harvest: Plants	Ecosystem condition; climate; hydrology	Ecosystem management; harvesting practices	Local demand
	Wild food harvest: Fish	Panne structure; hydrology; local biomass of fish populations; chemical state of water	Ecosystem and stock management; harvesting practices	Local demand
	Medicinal; cultural; other	Ecosystem condition; climate; hydrology	Ecosystem management; harvesting practices	Local demand
Regulating	Climate regulation	Structural state of marsh; sediment supply and depth; vegetation structure; atmospheric carbon concentrations	Ecosystem management; greenhouse gas emissions	Vulnerability to climate change
	Coastal flooding protection	Vegetation extent and structure; marsh structure; local tide and storm conditions	Ecosystem management	Areas of economic value at risk of flooding; Extent of other flood barriers (e.g. dykes)
	Coastal erosion protection	Marsh structural state; sediment depth; vegetation extent and structure	Ecosystem management	Areas of economic value; infrastructure; buildings and population in proximity to coast
	Sea-level rise protection	Marsh surface change rate (accretion, erosion), sediment availability	Ecosystem management	Areas of economic value; infrastructure; buildings and population in area at lower elevation than expected sea-level rise
Intermediate regulating	Water purification	Vegetation structure; soil depth; condition of soil	Ecosystem management; location, type and quantity of released pollutants	Location, type and volume of pollution emitted
	Habitat provision: Fish nursery	Ecosystem condition; panne structure; hydrology; biodiversity; presence of invasive species	Ecosystem and stock management and protection	Demand for biomass of species depending on the nursery habitat
	Habitat provision: Terrestrial	Ecosystem condition; local environmental conditions; presence of invasive species	Ecosystem management and protection	Other ecosystems demand for pest control; biomass; and functional requirements reliant on biodiversity
	Pollination	Ecosystem condition; pollinator abundance; vegetation types	Ecosystem management and protection	Location of crops benefitting from wild pollination
Cultural and non-use	Education	Extent; condition; structural state; landscape/seascape characteristics	Site access; ecosystem management	Education policy; research funding
	Recreation and tourism	Extent; condition; landscape/seascape characteristics	Site access; ecosystem management	Accessibility
	Spiritual and sense of place	Extent; condition	Ecosystem management; cultural practices	Local population count; accessibility
	Non-use	Extent; condition; services	Ecosystem/site management; societal connection to salt marsh	Knowledge and awareness of ecosystem and its services

Table 3b
Ecosystem services logic chain

Service type	Metrics or proxies for service quantification	Benefits	Main users and beneficiaries
Provisioning	Harvested biomass; sales data, foraging behaviour	Harvested products	Local population; restaurants and other businesses
	Harvested biomass; foraging behaviour	Harvested products	Recreational fishers; Local population and restaurants
	Harvested biomass; foraging behaviour	Harvested products	Local population
Regulating	Estimated carbon sequestration and carbon storage by area	Atmospheric greenhouse gas reduction leading to less climate change and fewer adverse effects	Global population, businesses and government
	Indicator using marsh width and length, wind speed, vegetation index, and topography	Decrease in storm surge damage and costs	Local population and businesses; infrastructure
	Indicator using marsh length and width, soil type and vegetation index	Lowers risk of flooding and removal of property; infrastructure and agriculture in coastal area	Local population and businesses; infrastructure
	Marsh surface change rate and sediment availability	Decreased future flood risk and need for expensive protective infrastructure; reduction in damage from sea-level rise	Local population and businesses; infrastructure
Intermediate regulating	Indicator using vegetation index, soil type and depth	Improved water quality in surrounding ocean and agricultural lands	Other ecosystems and beneficiaries of the services they provide
	Fishery recruitment biomass adjusted by percentage of nursery habitat area that is salt marsh	Continuing supply of provisioning ecosystem services in ocean	Industry and individual fisherpeople; indirect household consumption
	Count of species individuals in area; biodiversity index of key species using marsh	Continuing supply of pest control; supports other ecosystem services; intrinsic value of ecosystem	Local agricultural and built-up land (insect control by birds); other ecosystems
	Area of crops pollinated by wild pollinators using salt marsh	Reduced need for alternative forms of pollination, including paid pollination services	Local agricultural land (commercial, subsistence and household); indirect household consumption
Cultural and non-use	Indicator including count of salt marsh researchers, research grants, published papers and student theses and count of maintained salt marsh walks and education programs	Intellectual development, advancement of knowledge and understanding	Education and research organizations; general population especially students; industry
	Visitor numbers; recreation potential based on accessibility; citizen science and social media post counts	Physical and mental health of users	Local population; recreational organizations; tourists and tourism companies
	Condition indicator, potential supply based on accessibility	Sense of well-being; continued cultural practices; spiritual health of users	Local population
	Percentage of salt marsh area that is protected or conserved; count of species protected in Canada that use salt marsh	Sense of well-being	Global population

3. Conclusion and next steps

This paper has laid out a framework for the ecosystem accounts, proposing metrics that will provide a complete picture of salt marsh extent, condition and ecosystem services in Canada. Following this framework, accounts will be built gradually, addressing variables as prioritized by data availability, complexity, and importance. Once accounts are developed, they can be updated regularly as data, knowledge and modelling techniques improve.

Salt marsh is a dynamic and important coastal ecosystem that provides several key ecosystem services. It has historically been overlooked and its value to society has only recently become better understood. Because of this, there are many knowledge gaps relating to salt marsh. Salt marsh has been selected as one of the first focal ecosystems of the Census of Environment to highlight key data gaps and spur discussion on how to fill them to better understand this ecosystem.

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Appendix A – Extent methods

Salt marsh extent was calculated using the best available data sets with salt marsh delineation. Analyses were completed using ArcMap 10.8.1. Polygon, line, and point datasets were analyzed separately. Salt marsh polygons were extracted from respective datasets using the ecosystem classification unique to salt marshes or salt marsh vegetation types in each dataset as outlined in the respective metadata. Where necessary, Canadian salt marsh polygons were extracted from international data. Overlapping polygons were dissolved to create polygons that reflected maximum salt marsh extent boundaries except in New Brunswick where 2021 provincial data was used instead of international data. Line datasets were merged and the marsh shoreline classification was extracted. Marsh lines along the Great Lakes, beyond the southern reach of the Gulf of Saint Lawrence marine bioregion, and tributaries to the Gulf of Saint Lawrence were removed as they were deemed to be freshwater marshes. Canadian salt marsh points were extracted from international data. Points that were several kilometres inland or in the ocean were examined. They were removed if metadata did not provide an adequate explanation of their location, or manually moved nearer to the coast if other data sources confirmed the regional presence of salt marsh. Lines that intersected polygons and points within 1 km of polygons or lines were removed to create mutually exclusive records of salt marsh extent among the data types.

Appendix B – Glossary

Abiotic: non-living

Accretion: the process by which salt marsh soils are built—the gradual accumulation and cohesion of sediment and organic matter on the marsh surface

Attenuation: reduction of the force, effect, or value of something

Beneficiary: the user or receiver who derives advantage(s) from ecosystem services

Biomass: mass of organic matter in organisms, or a particular type of organism

Built-up areas: areas that are predominantly developed, such as road surfaces, buildings, urban areas, and industrial sites at a resolution of 30 m or greater

Carbon sequestration: the process through which carbon is captured from the atmosphere and stored in ecosystems

CHS: Canadian Hydrographic Service

Citizen science: the participation of the public in scientific research

Competition: the interaction between organisms or species where each are trying to use the same resources

Crowdsourced: data or information obtained by enlisting the services of a large number of people, typically through the internet

Cultural keystone species: a species that is of great importance to a culture or people

Digital elevation model (DEM): a model of the Earth’s surface

Dyke: an earthen ridge built to prevent flooding behind it, with one-way gates, called aboiteaux, that allow water drainage from the upland side but close to prevent flooding in the opposite direction

Ecosystem accounts: application of a spatially explicit accounting framework to environmental data to track change in extent, condition and ecosystem services

Ecosystem services: the ecosystem contributions to the benefits that humans gain from the natural environment

Elevation: elevation relative to mean sea level

Endemic species: species that only occur in a specific geographic location

Estuary: the ocean-tidally influenced transitional zone at the mouth of a freshwater river where it meets the ocean

Evapotranspiration: the process of evaporation and transpiration from the Earth’s surfaces and organisms that transfers water from the land into the atmosphere

Final services: ecosystem services from which humans directly benefit

GBIF: Global Biodiversity Information Facility

Herbivory: grazing on plants by animals

Hydroperiod: the length of time an area of land is wet

Indicator species: a species that is sensitive to environmental change whose condition can be used to indicate the health of its native environment

Intertidal: the coastal zone which is flooded between high and low tide

IUCN: International Union for Conservation of Nature

Keystone species: a species that has a large effect on its native environment

Marine edge: the edge of a marsh where it meets the ocean

Marsh: used interchangeably with “salt marsh”

Metric: Used here to describe a general method of measurement for a variable

Migration: describing the horizontal movement of a salt marsh, typically landward

NDVI: Normalized difference vegetation index

Panne: shallow depressions or pools in the salt marsh surface that hold water

Primary production: production of organic substances through the process of photosynthesis

Proxy: an indirect representation

Protected or conserved area: An area that is conserved and meets Aitchi 11 standards. A protected area is an area dedicated to conservation, while a conserved area can be dedicated to other objectives as long as it is effectively conserving biodiversity.

Recruitment: reaching a certain size or age that allows a fish to be caught

Rhizomes: underground stems

Salt marsh: any marsh that is periodically flooded with brackish or saline ocean waters

SEEA–EA: System of Environmental-Economic Accounting – Ecosystem Accounting

Sedimentation: the process of sediment deposition

Services: see Ecosystem services

Specialist species: species that can only survive in a specific range of conditions

Species richness: the number of unique species in a community

Terrestrial: describing land or land-dwelling organisms

Terrestrial edge: the edge of a marsh where it meets the land

Tidal hydrology: characteristics of or the study of Earth's tidal waters, including their movement. In this paper, used to describe the characteristics of tidal flooding including duration, frequency and depth

Tidal wetland: used interchangeably with salt marsh

Topography: the features of the Earth's surface

Variable: a component relating to ecosystem condition or ecosystem services which will be measured in some way in the ecosystem accounts

Vegetation community: a collection of different vegetation species that live together in a place

Vegetation index (VI): a calculation using multiple spectral bands from imagery that indicates vegetation structural properties

Wrack: a mat of plant debris, usually dead, that is floated by tides and can be deposited onto salt marshes