

Understanding multifunctional Bay of Fundy dykelands and tidal wetlands using ecosystem services—a baseline

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Abstract

We review what is known about ecosystem service (ES) delivery from agricultural dykelands and tidal wetlands around the dynamic Bay of Fundy in the face of climate change and sea-level rise, at the outset of the national NSERC ResNet project. Agricultural dykelands are areas of drained tidal wetland that have been converted to agricultural lands and protected using dykes and aboiteaux (one-way drains or sluices), first introduced by early French settlers (Acadians). Today, Nova Scotia’s 242 km system of dykes protect 17,364 ha of increasingly diverse land uses—including residential, industrial, and commercial uses as well as significant tourism, recreational, and cultural amenities—and is undergoing system modernization and adaptation. Different ES are provided by drained and undrained landscapes such as agriculture from dykelands and regulating services from wetlands, but more complex dynamics exist when beneficiaries are differentiated. This review reveals many knowledge gaps about ES delivery and dynamics, including around net greenhouse gas implications, storm protection, water quality, fish stocks, pollination processes, sense of place, and aesthetics, some of which may reveal shared ES or synergies instead of trade-offs. We emphasize the need to be open to adapting ES concepts and categorizations to fully understand Indigenous implications of these land use decisions.

Key words: Tidal wetland restoration, dike realignment, ecosystem service, managed realignment, salt marsh, trade-offs

1. Introduction

In the last few decades, North America has seen increased efforts to conserve and restore coastal habitats (e.g., [Zedler 2000](#); [Choi et al. 2008](#); [van Proosdij et al. 2010](#)). The northeastern North American tidal wetland area, including that of the Bay of Fundy system, has been in decline for centuries from

dyking, drainage, construction, and erosion (Gedan and Silliman 2009). Agricultural dykelands (also called agricultural marshlands) are areas of drained tidal wetland converted to agriculture using dykes and aboiteaux (one-way drains or sluices). In the 1600s, French settlers (called Acadians) to the Bay of Fundy used this technique to develop high-quality farmland in the Canadian provinces of New Brunswick (NB) and Nova Scotia (NS) (Butzer 2002). Currently, dykes protect agricultural production and a wide range of residential, industrial, and commercial uses owing to farmland abandonment and suburbanization as well as significant tourism and recreation (Sherren et al. 2016).

In many areas, current dyke dimensions are inadequate to protect these coastal land uses, given rising sea levels and storm surges expected with climate change (Lieske 2015; van Proosdij et al. 2018b). Such change and land-use dynamics have removed much of the remnant foreshore tidal wetlands (intact wetlands in front of dykes) that once served to protect the dykes themselves (Fig. 1), a process called coastal squeeze. Moreover, starved of rich sediments from the Bay for so long, many dykelands have subsided, making drainage on them increasingly difficult. The decision-makers that manage the dykes must decide where to reinforce, realign (shorten and pull back), or abandon dykes and related infrastructure. Realignment and abandonment of dykes provides opportunities to restore tidal wetland (Singh et al. 2007). Raising dykes to withstand sea-level rise widens footings, exacerbating coastal squeeze, so it cannot be paired with tidal wetland restoration and may in fact further reduce the extant amount. Early discussions of proposed modifications to individual tracts of dykelands have revealed tensions among governments, landowners, and other citizens, as well as challenges to policy coordination among the many government departments whose responsibilities overlap in these coastal landscapes (Rahman et al. 2019).

Reinforcing dykes and aboiteaux to maintain dykelands and restoring wetlands both affect the provision of ecosystem services (ES)—akin to what the Intergovernmental Panel on Biodiversity and Ecosystem Services now calls Nature's Contributions to People (*sensu* Díaz et al. 2018)—and, in some cases, result in disservices or unwanted consequences for society. ES are categorized as provisioning/material (e.g., food production), regulating (e.g., water filtration), and cultural/nonmaterial



Fig. 1. The Elderkin Dyke near the Windsor Causeway, NS, showing agriculture, dyke, and foreshore marsh from left to right. Photo: Graeme Matheson.

(e.g., recreation), all of which are built upon various amounts of ecosystem processes (supporting ES) and anthropogenic inputs (human and built capitals) (Rist et al. 2014). Disservices, in contrast, comprise reduction in any of these categories of services (Friess et al. 2020). Understanding ES dynamics is critical to informing site-based management decisions to reinforce dykelands or restore wetlands, as each involves trade-offs in services and disservices that often differ by beneficiary.

Wetlands help regulate climate, water storage, erosion, natural hazards, soil formation and nutrient cycles (Mitsch and Gosselink 2000; Mitsch et al. 2013). Mature coastal wetland restoration may provide more effective protection than hard infrastructure (e.g., dykes) against sea-level rise and storm surges and create more resilient coastal communities (Temmerman et al. 2013; Narayan et al. 2017; Van Coppenolle and Temmerman 2019). However, trade-offs with human well-being exist (e.g., dependent on adjacent land management; Chmura et al. 2016), as well as a lag before tidal wetlands deliver the full range of ES for which their restoration is endorsed (Chmura et al. 2012; Smith et al. 2017). Nonmaterial benefits, such as education and recreation, can accrue from wetlands as well (Chen et al. 2020), including for First Nations, whose historical and cultural practices may be particularly linked to such threatened ecosystems (Berkes and Davidson-Hunt 2006).

Alternatively, dykelands can be maintained and (or) raised, allowing for the provision of a suite of ES not limited to agriculture. Despite the natural buffering value of tidal wetlands, many citizens perceive dykes as providing the best storm protection and a range of other anthropogenic services (*sensu* Rist et al. 2014) that require some human input to achieve (e.g., food provisioning, recreation) (Sherren et al. 2016). The capacity of NS to augment its food supply using dykelands is often discussed in the context of dyke overtopping and resultant flooding of the low-lying Chignecto Isthmus (much of it dykeland) through which most food arrives in the province (Rapaport et al. 2017). The dykelands, dykes, and aboiteaux are still strongly associated with the Acadian culture, which persists in the region despite their forced deportation in the mid-1700s (Desplanque 1982). The region is also an Important Bird Area and a Western Hemisphere Shorebird Reserve Network site, providing an important stopping ground for migratory ducks and shorebirds, the latter declining in number (Rosenberg et al. 2019). While most of the birds are attracted to tidal wetlands, dykes provide access for watching them. Such everyday uses of and attachments to dykes and dykelands drive local resistance to their loss (Sherren et al. 2016).

A new five-year Canadian research network called NSERC ResNet has been initiated for monitoring, modelling, and managing Canadian ES. The project explores the utility of ES thinking for sustainably managing working landscapes—those used to produce food, energy or fibre—given competing land uses and human values. The Nova Scotian Bay of Fundy coast is one of its six case study landscapes. NSERC ResNet will provide our team an opportunity to: (i) fill knowledge gaps about the implications of specific land-use decisions to ecosystem integrity and human well-being, (ii) inform dykeland and tidal wetland decision-making, and (iii) contribute to national ES assessments and techniques. This paper represents a baseline synthesis of our incomplete understanding of point (i) as we initiate our collaboration: what ES are provided by dykelands and tidal wetlands in the Bay of Fundy? Nothing comparable currently exists to inform our work. The complexity of the above research question excluded the possibility of a systematic review. For instance, most of the work we draw upon does not employ ES language and would be missed if we used such keywords to collect relevant material. Instead, we leveraged the shared expertise of a diverse team to develop this narrative review. Research gaps we have identified in the region mean that much of what we present is necessarily inferred from literature from other geographies. Finally, we present a conceptual assessment of ES knowledge and trade-offs; the literature cannot yet support a robust quantitative analysis nor would we consider one especially informative for the full range of services being considered.

We begin with an introduction to the Bay of Fundy dykeland context before summarizing what we know and do not yet know about delivery of final ES along three categories: material

(provisioning), regulating, and nonmaterial (cultural). We conclude with a discussion of the more complex dynamics potentially at play in dykeland–wetland decisions, foreshadowing the work of this case study landscape within ResNet. Throughout, we focus on the NS side of the Bay of Fundy where most of our empirical experience and expertise lies; processes and lessons may be applicable elsewhere.

2. The Bay of Fundy dykeland–wetland context

2.1. Land-use history to today's challenges

Nova Scotia's coasts have long been occupied. The Mi'kmaq (First Nations) relied on coastal settlements for fishing (Hornborg 2008). Records of early contact with European explorers and fishers along the Atlantic coast date back to the 16th century, but it was in the 1600s that permanent French settlers, later called Acadians, arrived in the Bay of Fundy. The Acadians constructed dykes and aboiteaux to drain coastal wetlands around the Bay of Fundy for agriculture instead of clearing upland forest where soils are relatively shallow (Butzer 2002). Stories exist of the Mi'kmaq helping Acadians with dyke construction (Gerald Gloade Sr., Mi'kmaewey Debert Cultural Centre, personal communication 2018), although this may have been to ensure the dyke locations avoided important marsh and creek locations for Mi'kmaq and the ES those sites provided. After the English eventually won the mainland in 1713, many Acadians were deported. The Treaties of Peace and Friendship that the Mi'kmaq signed with the English did not involve the ceding of land rights, but Mi'kmaq were forced onto 13 reserves, many inland (Paul 2006).

The farming and expansion of the rich dykelands were undertaken by the Canadian English, Loyalist New Englanders, who relocated to British territory after the American War of Independence, and later settlers from the European continent. Responsibility for the integrity of the dyke system shifted from landowner cooperatives to government in the mid-20th century through the federal Maritime Marshland Rehabilitation Act of 1948, with responsibility subsequently passed on to the provinces in 1970 (Sherren et al. 2016). Under the *Nova Scotia Agricultural Marshland Conservation Act* 2000, c. 22, s. 1., the Minister of Agriculture has the powers to: “Reconstruct, repair, operate and maintain any works for the protection, drainage and improvement of marshland for agricultural purposes” (Government of Nova Scotia 2000). These agricultural dykelands remain some of the highest quality farmland in the region. The Nova Scotia Department of Agriculture (NSDA) owns and maintains the dykes and aboiteaux but generally not the land behind. The landowners within each of the 81 administrative units of Nova Scotia dykelands (Fig. 2) are members of Marsh Bodies, incorporated to manage each system in partnership with the NSDA, including deliberating and voting on management changes. Originally built to protect agricultural land and to support farming practices, dykes today are increasingly protecting landscapes that are agriculturally inactive (13.4%) or that are being used for nonagricultural purposes (16.2%) (NSDA 2019).

It has been estimated that the Atlantic region has lost over 69% of its coastal tidal wetlands in the Bay of Fundy largely due to dyking (Hanson and Calkins 1996) and construction of causeways and associated tide gates (van Proosdij and Page 2012). In November 2019, there were 242 km of dykes, 252 aboiteaux, and 17,364 hectares and 7473 distinct properties of dykelands in Nova Scotia (NSDA 2019); only 70% of that area remained in agricultural production. The towns of Truro, Amherst, Windsor, and Wolfville are at least partially protected by agricultural dykes. In many coastal communities, the dykes provide flood protection and routes for coastal access, including by walkers, runners, cyclists, birdwatchers, hunters, and fishers; such uses can unintentionally damage dyke infrastructure (Chen et al. 2020). Acadians originally designed agricultural dykes to allow for “tiding”: tidal inundation every few years to avoid subsidence. Modern dykes are not designed this way, so overtopping can threaten the integrity of the protected agricultural lands and infrastructure. NSDA

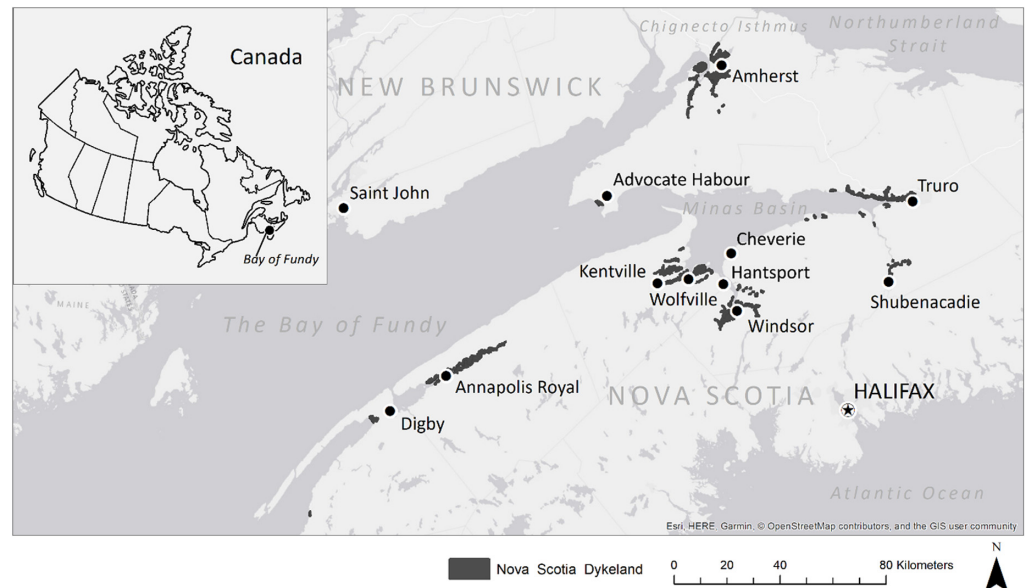


Fig. 2. Dykeland locations on the Nova Scotia side of the Bay of Fundy, including key population centres and geographic features. Map: Yan Chen.

has developed engineering principles for dykeland construction and maintenance in the face of climate futures, as well as a dyke classification based on “consequence of failure” to aid (along with flood mapping) in the prioritization process for dykeland decision-making. The Bay of Fundy dykelands are multifunctional landscapes set within an already dynamic, mega-tidal natural system that is facing increasing challenges as well as demands from a changing climate. NSDA does not presently have the resources to raise all Nova Scotia dykes to heights that would be effective against future sea levels, and in many cases it may not even be technically feasible to keep raising the dykes. As a province, NS must begin to make difficult decisions about which dykes can and should be raised (van Proosdij and Page 2012).

The practice of re-introducing tidal flow to former dykelands, or managed realignment, has been actively performed in many places (French 2001; Bennett et al. 2020). Ducks Unlimited Canada began constructing freshwater wetlands on dykelands or impounding salt marshes with new dykes in the 1980s. In the mid-2000s, regional dyke decommissioning and tidal marsh restoration began, including on some Ducks Unlimited Canada impoundments (Bowron et al. 2012), but the first managed realignment project involving construction of an inner dyke in NS happened in 2018. Such restoration was begun in the Bay of Fundy to decrease the cost of maintaining failing dykes and (or) restore tidal wetland habitat (Singh et al. 2007). Wetland restoration remains primarily a response under provincial and federal wetland policies to compensate for wetland alteration and destruction (for instance by road construction) and increase wetland ES; the NS Wetland Conservation Policy has the primary goal of long-term net gain in salt marsh habitat (Government of Canada 1991; Rubec and Hanson 2009; Government of Nova Scotia 2011). Dykeland can be restored to tidal wetland either by actively dismantling dykes or through passive neglect, or by realigning (pulling back) the dyke where protection needs remain. Creating foreshore wetlands reduces coastal squeeze (Pontee 2013), allowing for more dynamic and naturally regulated shoreline movement and helping to protect infrastructure behind, including any realigned dyke. The restorations undertaken to date represent suitable sites for testing ES supply at various stages of maturity (Bowron et al. 2012; Boone et al. 2017).

2.2. Geographical setting

Local ecosystems and biodiversity are the engines of ES delivery (Close et al. 2009). The structure and functioning of the Bay of Fundy dykelands and tidal wetlands, including their vegetation, climate, hydrology, coastal zone dynamics and geology, determine the ES and disservices at play.

2.2.1. Vegetation

Tidal wetland vegetation in the Bay of Fundy shares a suite of repeating species common across the coast of northeastern North America (Bowron et al. 2012), dominated by native salt-tolerant perennial grasses (Porter et al. 2015). Three main zones are recognized: low marsh (lowest elevation) frequently inundates and is dominated by smooth cordgrass (*Spartina alterniflora*), high marsh inundates periodically and is dominated by salt hay (*Spartina patens*) or black grass (*Juncus gerardii*) and a suite of other native herbaceous perennials, and brackish marsh communities have a range of dominants depending on factors such as disturbance and freshwater influence (Porter et al. 2015).

Dykeland vegetation can be divided into the foreshore, the dyke itself, and the protected area inside the dyke. Foreshore vegetation often contains tidal wetland species, with specific communities largely determined by elevation within the tidal frame and freshwater influence. The dyke itself is covered with perennial upland grasses and is usually mown, with weeds such as wild chervil (*Anthriscus sylvestris*) and giant hogweed (*Heracleum mantegazzianum*) controlled with herbicide. Behind the dyke, row crops, hay fields, or pasture represent typical active uses of lands. If left to extended fallow, a variety of “old-field” vegetation types can occur, with soil moisture conditions a likely driver of the types found. This old-field vegetation tends to have a much higher proportion of non-native, diverse plant species than tidal wetlands but is dominated by perennial grasses and forbs. Unmanaged vegetation immediately adjacent to the dykes or between actively farmed areas commonly contains old-field vegetation. Predictable species and successional trajectories for dykelands left fallow are apparent, but published studies of them are lacking.

2.2.2. Climate and hydrology

Relative sea-level rise for the Fundy region is projected to be among the highest in Canada (Manson et al. 2019), and could range from 77 cm to 120 cm by 2100 compared to 1985 (James et al. 2015). Along with this rise comes the added vulnerability of the region to storm surges, which can already overtop some dykes (van Proosdij and Page 2012). It is estimated that 82% of extant Bay of Fundy dykes would be overtopped by a “1 in 50 year” storm by 2050, impacting 808 km of roads (van Proosdij et al. 2018a). In addition, dykes and associated aboiteaux that are meant to protect low-lying coastal lands from tidal flooding can actually exacerbate flooding by restricting freshwater drainage, as is the case with chronic flooding events in Truro, NS (Marvin and Wilson 2016). The Bay of Fundy coast is relatively wet, compared with other places in the region (see, for instance, Rivard et al. 2007), and rainfall events in the region are expected to become more severe and more frequent in future (Richards and Daigle 2011).

Whereas dykes are in place to prevent seawater inundation, periodic inundation of seawater by tides drives tidal wetland functions and the ES they support (e.g., Byers and Chmura 2014). Tidal wetlands are recharged by saline water through periodic flooding of the wetland surface during high tides as well as by freshwater through groundwater, precipitation, and overland runoff (Harvey et al. 1987; Nuttle and Hemand 1988; Byers and Chmura 2014). Tidal inundation, low permeability of the marsh sediment, and their intertidal elevation contribute to shallow water tables, influencing a tidal wetland’s capacity to sequester and store carbon from the atmosphere and maintain elevation in the face of sea-level rise. In contrast, the purpose of dykelands is to prevent tidal flooding, and as such, dykelands have extensive freshwater reserves, fed through precipitation and recharged from uplands.

2.2.3. Coastal zone dynamics

The dynamism of the Bay of Fundy is important to understand for its coastal management. The Bay's geometry creates tidal resonance, resulting in mega-tidal conditions with the tidal ranges of up to 17 m (Garrett 1972; Godin 1988) and extensive intertidal zones grading from sand to mudflats and vegetated wetland surfaces (Desplanque and Mossman 2004), making them unique in the context of coastal restoration. The Bay of Fundy has a relatively high but spatially variable sediment supply, which is essential in helping its tidal wetlands keep pace with sea-level rise (storm buffering ES) and which influences restoration trajectories. Suspended sediment concentrations range from $< 50 \text{ mg}\cdot\text{L}^{-1}$ in the lower Bay near Annapolis Royal to greater than $70,000 \text{ mg}\cdot\text{L}^{-1}$ in tidal rivers in the Minas Basin near the turbidity maximum (van Proosdij et al. 2018c). Much of this material is resuspended from mud and sand flats by waves, originating from erosion of sedimentary cliffs and foreshore marsh deposits (Wilson et al. 2017). Foreshore marshes, originally stimulated by dyking, typically exhibit patterns of erosion and accumulation at the Basin scale (Ollerhead et al. 2005; van Proosdij et al. 2018c) and are influenced by dykeland management practices and natural processes (e.g., storm activity, sea-level rise, river discharge, meandering tidal rivers) (Matheson 2020). Preservation and enhancement of foreshore marsh is now recognized and accepted as best management practices for decreasing dyke vulnerability (Vuik et al. 2016; van Proosdij et al. 2018c; Vuik et al. 2019).

2.2.4. Geology and hydrogeology

The bedrock geology in the Bay of Fundy region largely determines the availability of water in deeper groundwater systems (aquifers), whereas surficial geology affects shallow groundwater resources and salinized soil dynamics. The surficial geology of the region is characterized by glacial lake deposits (sand, silt, and clay), glacial river deposits (sand and gravel), glacial till, and marine deposits (Rivard et al. 2012). These deposits are generally not productive aquifers for pumping water; however, they play an important hydrogeological role in providing groundwater recharge to deeper bedrock aquifers and also influence saltwater intrusion dynamics. The majority of domestic water supplies in the region have historically been obtained from wells constructed in glacial till (Trescott 1969). However, the towns of Wolfville and Kentville also use surficial sediments as part of their water supply (Rivard et al. 2007). Because Atlantic Canada is at the periphery of the continent, the depression of the ground level due to glacial isostatic adjustment is resulting in the pronounced relative sea-level rise rates for the region (Savard et al. 2016), which in turn influences mixing between the Bay and coastal aquifers as well as the frequency and intensity of dyke overtopping and coastal erosion. In general, understanding the groundwater systems and saltwater flushing dynamics following dyke overtopping is key as fresh groundwater is used extensively in the region for drinking water and irrigation supply.

2.3. Governance, stakeholders, and key actors

Coastal areas in NS are a crowded jurisdictional and occupational space, but also a complex social, cultural, and organizational setting. Many groups play a role in the use and management of the coastal zone, and these can often come into conflict, as well as collaborate and innovate to undertake dyke realignment and (or) tidal wetland restoration (Rahman et al. 2019). Formal governance is complex, including key Provincial departments, such as Agriculture (farming, land protection), Environment (wetland regulation, climate adaptation, coastal protection), Transportation and Infrastructure Renewal (transportation infrastructure), and Lands and Forestry (beaches, hunting, wetland ecology, biodiversity), and at the Federal level the Department of Fisheries and Oceans (fish and fish habitat) and Environment Canada and Climate Change (wetlands, migratory birds). Other important players include departments related to Municipal Affairs (flooding), Aboriginal Affairs (First Nation rights), Acadian Affairs (culture and diaspora), and Communities, Culture and Heritage (tourism,

archaeology), as well as nongovernment organizations and nonprofits (e.g., Ecology Action Centre, Ducks Unlimited Canada), and practitioners of coastal restoration (e.g., CBWES Inc., CBCL Limited) (for more fulsome descriptions, see [Rahman et al. 2019](#); [Sherren et al. 2019](#)).

While dyke decisions pose a clear challenge to those who live and (or) work on dykelands (e.g., farmers and other Marsh Body members), the question of dykeland futures is perhaps most complicated for members of the Mi'kmaw (First Nations) community because it represents a trade-off between the integrity of the archaeological resources often located in dykelands and the potential restoration of ES that nourish today's Mi'kmaw culture and society. Mi'kmaw governing bodies are heavily engaged in advocacy for coastal restoration projects and monitoring, including in erstwhile dykelands, with a strong focus on fish passage between ocean and river. At the same time, the Mi'kmaw Rights Initiative (KMKNO, Kwilmu'kw Maw-klusuaqn) has the mandate to protect the archaeological resources often present in dykelands that represent heritage as well as evidence of occupation, and that could potentially be damaged by inundation or earth-moving activities typical of dyke realignment. Debates between stakeholders and rights holders on these issues can be difficult.

Finally, all residents of the Bay of Fundy coast are affected by the decisions to be made, whether they come from Mi'kmaw heritage, Acadian, Planter, or other early or more recent settler groups. Many coastal occupants and land users rely on dykes for their protection, as well as sense of place, recreation, and livelihoods. Media coverage of conversations about dyke realignment and tidal wetland restoration have received mixed responses among affected residents since the first intentional salt marsh restoration project began in the province in 2005 in Cheverie, NS ([Bowron et al. 2012](#)). Residents in towns like Hantsport and Advocate Harbour have been recently upset by discussions of possible realignment of dykes or the removal of large tidal barriers near their towns, sometimes so effectively as to weaken political will to carry out such decisions. In other settings, such as Truro, such changes have not yet been controversial ([Sherren et al. 2019](#)). Path dependency (when what has been done in the past constrains future options) is not just a technical phenomenon, but a psychological one, as residents anchor in their current landscape norms ([Sherren et al. 2017](#)). Robust engagement is critical in such situations, but there has been little social science conducted in the dykelands to inform it.

3. Ecosystem service provision and knowledge gaps

Many ES frameworks are aimed at economic assessments of the environment ([de Groot et al. 2012](#); [Davidson et al. 2019](#)), in which coastal wetlands are highly valued in part because of their rarity. There have been local attempts to calculate economic value for our two ecosystems, particularly the wetlands, but this too has suffered from poor local data. One early NS assessment took one of the lower coastal wetland ES values calculated in the United States to calculate annual losses to the province as a result of the estimated 62% of tidal wetlands dyked or otherwise destroyed (19,958 ha or \$706 million) and “earnings” from those extant ([Wilson 2000](#)). In another study, [De Maio Sukic \(2001\)](#) found that the mean compensation that private landowners on the NB side of the Bay of Fundy would be willing to accept to contribute a hectare of tidal wetland to a conservation program was \$1004.22. A decade or so earlier, [Stokoe et al. \(1989\)](#) explored the public willingness to pay for a hypothetical conversion of the Minudie dykeland near Amherst to wetland and found values ranging from \$2.50 per ha for nonwetland-using naturalists to \$25 by members of the general public who use wetlands. According to the Canadian Environmental Valuation Reference Inventory there has been no work on this financial question in the last two decades in this region, perhaps in part because such valuations have been shown to be so variable and to have little impact on coastal decision-making ([Laurans and Mermet 2014](#); [Marre et al. 2016](#)), though it has been applied in similar contexts for managed coastal realignment in the United Kingdom ([Luisetti et al. 2011](#)).

We take a more conceptual approach here, inspired by the ES assessment of deltas by [Adger et al. \(2018\)](#). This helps us to follow ES delivery from the elements comprising the two main landscape alternatives—dykelands and wetlands—through a combination of ecosystem processes (otherwise known as supporting ES) and anthropogenic inputs (human and manufactured capital) to specific services ([Fig. 3](#)). Some of those linkages are well-understood, and others less so (see dotted lines in [Fig. 3](#)). The landforms in question, moving from inland to ocean, include various amounts of dyke-land and wetland elements (inside boxes in [Fig. 3](#)). A “unit” of dykeland generally comprises: inactive/fallow, cultivated, or grazed dykeland (other dykeland land uses are outside this model); ditches that drain freshwater from it thanks to careful forming of the dykeland; aboiteaux that allow freshwater to escape at low tide and prevent saltwater coming in at high tide; the dyke structure itself; and the borrow pit on the ocean side from which material was excavated to construct it. Tidal wetland is considered to comprise a range of vegetation types from brackish to low marsh (see Section 2.2.1), some of it forming a protective foreshore for the dyke. Conversion from tidal wetland to dykeland is no longer permitted in NS, beyond the wider footings that may accompany dyke raising. Conversion from dykeland to wetland can in rare cases be done by breaking a gap in the dyke and re-engineering natural drainage to the whole area, but it is more often partial, where a new dyke or dyke section is constructed upland from the water to continue to protect land behind while leaving space in front for restoration of tidal flow. A preliminary listing of ES delivery by land-use alternative ([Table 1](#))

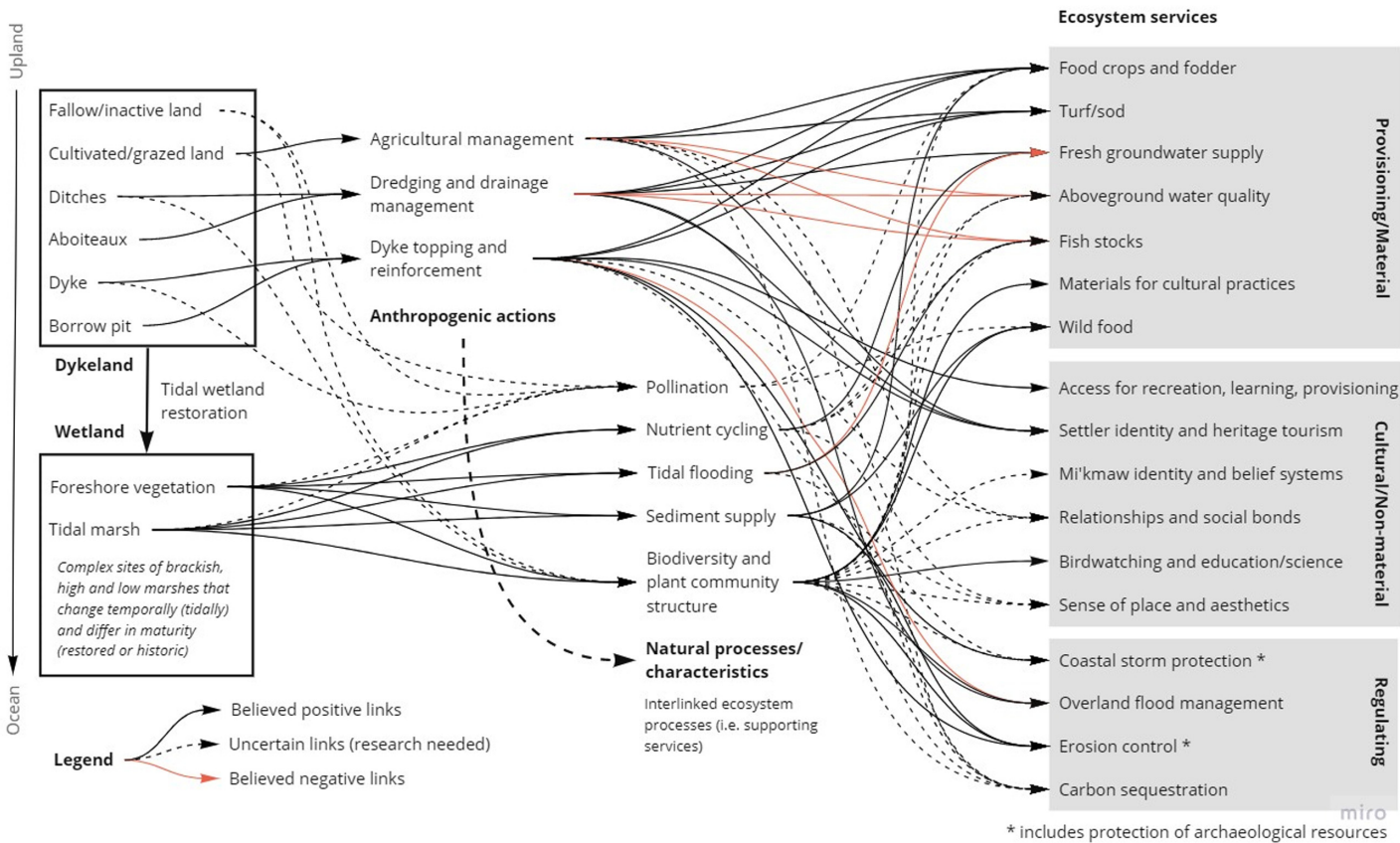


Fig. 3. Conceptual diagram illustrating the complex flows of ecosystem services (black) and disservices (red) from dykeland and wetland systems, including via anthropogenic activities and natural processes, highlighting knowledge gaps (dotted lines). Additional details can be found in [Supplementary Material Table S1](#); dykeland- and wetland-specific versions can be found in [Supplementary Material Fig. S1](#).

Table 1. Trade-offs and synergies between dykeland maintenance/reinforcement and wetland restoration, with knowledge gaps in italic text.

Ecosystem service category	Dykeland maintenance	Shared ecosystem services or synergies	Wetland restoration
Provisioning/ material	Food crops and fodder Turf/sod	Fresh groundwater supply (where significant foreshore marsh also present)	Materials for cultural practices Wild food <i>Fish stocks/commercial fishing</i>
Regulating	—	Overland flood management Erosion control <i>Carbon sequestration</i> <i>Coastal storm protection</i>	<i>Aboveground water quality</i>
Cultural/immaterial	Access for recreation, learning, and provisioning Settler identity and heritage tourism	<i>Sense of place and aesthetics</i> <i>Relationships and social bonds</i>	Birdwatching and other education/science <i>Mi'kmaw identity and belief system</i>

suggests dyke management decisions will require careful weighing of costs and benefits, over time and space, and for a range of beneficiaries. The wider context of climate change and the Canadian context of reconciliation with Indigenous people over injustices both provide important dimensions to the question of dykeland–wetland futures.

3.1. Material ecosystem services

Material services are often treated as a stock of raw materials (i.e., goods) when they are really the reproductive capacity of ecosystems (Farley 2012). In the context of dykelands and tidal wetlands, the key material services are food, freshwater, and biomass. Some of these services overlap with non-material and regulating services discussed later.

Food is clearly provided from dykeland systems in the form of crops and livestock; that is what they are designed for, and today dykelands provide a good share of NS’s highest quality (Class 2) agricultural land (Millward 1999). Actively farmed dykelands (70.7%) are roughly three-quarters field crops and one-quarter pasture (NSDA 2019). Significant development pressures exist on dykelands, particularly those near larger population centres, including farmland abandonment associated with various socio-economic dynamics, such as inheritance and succession issues and the high cost of farmland for new farmers (Clowes 2016). Dykelands may also be used for turf/sod production. As there is more flooding at the low-lying Chignecto Isthmus which serves as a critical transportation route for fresh food, dykelands may be important for future food supply (Rapaport et al. 2017).

Dykeland freshwater resources and dependent crops are threatened by surface and subsurface salt-water intrusion, though little research on these dynamics has been done in the Fundy area (Kennedy 2012). As noted above, large storm events that overtop dykes can cause extensive flooding of dykelands, threatening agricultural productivity and damaging infrastructure (Yang et al. 2013; Elsayed and Oumeraci 2018). Because dykes act as a barrier between land and sea, they can also prevent the seaward drainage of flood water, threatening crop yields and the water quality of irrigation wells (Yang et al. 2013). Dykeland groundwater quality is also threatened by sea-level rise. Even if the dykes are able to protect against the ocean, as sea levels rise, the groundwater table responds by increasing in elevation proportional to the magnitude of sea-level rise (Rotzoll and Fletcher 2013). In low-lying dykelands with shallow water tables, a rising groundwater table may intersect the ground surface, causing complete soil saturation that can be harmful to crops and infrastructure.

Furthermore, such saturated soil is prone to flooding. Dykelands are particularly vulnerable to groundwater saturation, as the process of draining wetlands and lowering water tables for agriculture causes organic matter to decompose and land to subside. They are also subsiding because their sediments are no longer recharged from the muddy Bay of Fundy as was occasionally done (intentionally and unintentionally) during early settlement.

Apart from a few wetland species collected for traditional food purposes (e.g., *Salicornia* spp. also known as pickleweed or samphire), tidal wetland food provision is related to fishing and hunting. Wild food represents provisioning services, but the harvesting activities can be recreational services, depending on circumstances. Little is known about the importance of tidal wetlands to Bay of Fundy commercial or recreational fisheries (e.g., compared to New England (Taylor 2008)), such as striped bass (*Morone saxatilis*) which are critical to the local gross domestic product, though the nursery function of low marsh is well known (Baker et al. 2016). There are important commercial fisheries for herring (*Clupea harengus*) and American eel (*Anguilla rostrata*) in NS as well as an important Indigenous fishery for gaspereau/alewife (*Alosa pseudoharengus*) and shad (*Alosa sapidissima*) (Fisheries and Oceans Canada 2018). All such species have been found in various life stages in tidal wetlands, including juvenile stages indicating nursery use (e.g., Eberhardt et al. 2015). Although the habitat used by juvenile lobsters is still somewhat of a mystery, there is evidence that “peat reefs” (chunks of peat colonized by *Spartina alterniflora* that have broken off from the main salt marsh surface and settled in adjacent subtidal marsh channels) may be important nursery habitats for juvenile lobsters (Able et al. 1988). Given the importance of the lobster fishery in NS, the province’s most valuable seafood export at over \$700 million annually (Fisheries and Oceans Canada 2018), the condition of the habitats that support lobsters has important implications for the valuation of ES.

Hunting remains a key activity in North America (Heffelfinger et al. 2013; Arnett and Southwick 2015), contributing approximately 40 billion dollars to the North American economy and helping to sustain waterfowl numbers through collaborations with groups like Ducks Unlimited (Cooper et al. 2015), although hunting’s relative importance is declining compared with various forms of wildlife watching (Hill et al. 2010). In Maritime Canada, dykelands and tidal wetlands alike have a long and storied tradition as key habitats and hunting locations for waterfowl (Rusch et al. 1989; Ringelman et al. 2015), but demographic shifts and urbanization have reduced the number of hunters and the hunting economy in a decades-long pattern of decline (Canadian Wildlife Service Waterfowl Committee 2019).

Beyond the above provisioning services, Mi’kmaq also use tidal wetlands for the collection of many plants for various traditional purposes, but these are not documented in ways that facilitate integration with botanical and ES knowledge (e.g., using different names, oral traditions). Sweetgrass (*Hierochloa odorata* or *Kjimskiku*) is used for smudging ceremonies during significant events, and reportedly sea lavender (*Limonium*) is used for ornamental purposes. In brackish marshes the cattail (*Typha* sp.) is also a traditional food source (i.e., roots, young shoots, inflorescences), the leaves of which can also be woven to make mats and baskets. Numerous medicinal uses would exist for such tidal wetland plants as well, but such knowledge is carefully managed by Elders, to protect the ecosystems and the culture alike.

3.2. Regulating ecosystem services

Regulating services are those that moderate key environmental processes, maintaining the structure and function of ecosystems around long-term mean conditions (Brander et al. 2013). Indicators of regulating services can be straightforward to select but are challenging to operationalize due to inadequate knowledge on how ecosystem functions generate corresponding services (Reed 1995; Hattam et al. 2015). The regulating services we explore here are pollination, storm protection, flood reduction,

erosion control, water filtration, and carbon sequestration. Some of these have relationships with agricultural provisioning (pollination and erosion control), and there are needs for further research in this region.

Wild pollinators of crop plants in NS, such as blueberries, beans, peas, squash, and pumpkins, mainly consist of bees, butterflies, and hoverflies (Larson et al. 2001). The persistence of wild pollinators in agricultural landscapes requires food and nesting resources. Food resources include pollen and nectar produced by crop plants, but most pollinator species require these resources outside of the narrow flowering window of crop plants so adjacent habitats that can provide floral resources at other times of year are crucial (Mallinger et al. 2016; McCallum and McLean 2017). Nesting resources differ by pollinator species, and can include specific larval host plants (e.g., for butterflies), bare soil (e.g., for ground-nesting bees), or woody debris (e.g., for cavity-nesting bees) (Moissett and Buchanan 2010). The earliest ecological accounts suggest that tidal wetlands have low value for pollinators since the most abundant plants are wind-pollinated and do not produce floral resources (Ganong 1903), but pollinator assemblages in tidal wetlands have not been sampled in the region. We expect that high and brackish marsh zones contain the most resources for pollinators as lower inundation rates may allow ground-nesting bees to nest and there is a greater diversity of plant species that are insect-pollinated compared with low marsh zones. New tidal wetland habitat resulting from managed realignment or other restoration activities may also contain dead trees or shrubs that could represent importing nesting resources for wild bees. On dykelands, foreshore vegetation is likely to provide few resources for pollinators, but dyke tops and sides and spontaneous vegetation on the inland side of dykes tend to have a wide variety of plant species that are insect pollinated (Sheffield et al. 2013), so we suspect that dykelands may support larger and more diverse populations of bees and other beneficial insects.

Other than pollination, tidal wetlands are renowned for providing a wide range of regulating services, although wetland restoration may not be valued for these services among some stakeholders. Along with climate change itself, restoration reintroduces saltwater further inland through both surface and subsurface pathways, affecting freshwater resources but on shorter timescales (Willemsen et al. 2020). Wetland vegetation and a range of other biogeochemical processes also remove nutrients, such as anthropogenic nitrogen and phosphorous from land uses, as well as other upland contaminants moving to the Bay (Molnar et al. 2012). With respect to storms and resilience, however, tidal wetland processes help them survive and even thrive under extreme or changing conditions. The dense vegetation of tidal wetlands decreases wave energy, minimizing overland flooding due to storm events (Möller and Spencer 2002; Vuik et al. 2016). Tidal wetlands are resilient to sea-level rise through vertical accretion (build-up) and horizontal migration, which occurs as tidal channels deliver water and suspended sediment to the marsh platform where dense vegetation diminishes water velocity and enables sediment settlement and mineral accumulation (Temmerman et al. 2013; Narayan et al. 2017). While measurements of surface elevation change have been conducted as part of wetland habitat compensation projects (van Proosdij et al. 2010; Bowron et al. 2012), systematic analysis and comparison to natural marshes is limited. This is particularly relevant for sites within the lower Bay of Fundy with lower sediment supply or sites with poor drainage affecting below-ground (root) processes.

Tidal wetlands can sequester large amounts of carbon (C) relative to most terrestrial ecosystems (McLeod et al. 2011), including freshwater wetlands, a phenomenon also called blue carbon. The role of tidal wetlands as carbon sinks is due to two key features of these ecosystems: (i) C produced elsewhere can be sequestered (captured and stored) by tidal wetlands due to deposition and accretion of the marsh surface over time, and (ii) *in situ* productivity can be high and decomposition rates tend to be low due to flooding and high salinity. Conversion of tidal wetlands into agricultural land often

results in a loss of stored C and a net increase in greenhouse gas emissions (through fertilizer-induced N_2 release and enhanced CH_4 production in soils; Tan et al. 2020). We expect that tidal wetlands will generally provide more value related to mitigation of climate change than dykelands (Connor et al. 2001; Burden et al. 2013), but local data on C stocks and offsets from non- CO_2 greenhouse gases in the diversity of dykeland habitats present in the region are lacking (Roughan et al. 2018).

Research in other regions suggests the value of C sequestration services increases over time in restoring tidal wetlands (Abbott et al. 2019; Burden et al. 2019; O'Connor et al. 2020), so a key knowledge gap in our landscape is the relationship between C storage and time since restoration of tidal flow. The restoration process can cause short-term release of N_2O and CH_4 , both greenhouse gases that counteract the climate benefits, but studies suggest that C storage will outweigh these emissions over the long term (Wollenberg et al. 2018a). The relative contribution of C present in suspended sediment compared with C produced by C fixation by local vegetation is also unknown. While initial reports suggest that plant production on new marshes is a minor contributor to soil organic C stocks (Wollenberg et al. 2018b), we require information from multiple sites, sediment depths, and vegetation types to create a complete account of C stocks in regional tidal wetlands. As plant density and coverage are key determinants of sediment accumulation and local biological production, understanding the dynamics of plant establishment and subsequent decomposition in marsh restoration is also important. We need more research on the abiotic and biotic factors that determine establishment rates of plants during restoration, including the importance of mycorrhizal colonization in allowing tidal wetland grasses to colonize and flourish (Cooke and Lefor 1990; d'Entremont et al. 2019).

Feedbacks between plants and other environmental factors may play a major role in determining carbon sequestration rates as well. Tidal wetland organic matter decomposition is increased by input of nutrients, such as nitrate from agricultural fertilizer use, and this might mean less rather than more burial of organic C rich sediment (Bulsecu et al. 2019). It could also reduce the belowground root biomass that stabilizes sediments, increasing wetland susceptibility to coastal erosion (Deegan et al. 2012). In other words, with pollution, tidal wetlands could switch from being C sinks to sources.

3.3. Nonmaterial ecosystem services

Nonmaterial services are by definition intangible and experienced differently by different individuals, a subjectivity that makes it challenging to understand delivery and identify beneficiaries (Daniel et al. 2012; Small et al. 2017). Such services tend to be difficult to enumerate or disentangle, but are key to the formation of sense of place and certainly not immaterial to decision-making in dykeland-wetland settings or elsewhere (Scholte et al. 2016; Margaryan et al. 2018). Changes in them can be deeply felt and fuel resistance to landscape change. Most nonmaterial services are experienced in “bundles”, which means they can foster multi-use, multi-benefit plans that appeal to divergent preferences within the community (Milcu et al. 2013). Neither NS tidal wetlands nor dykelands have been well studied for this purpose.

The easiest nonmaterial services to assess are those that come with a market element that makes them trackable, such as tourism and recreation. For instance, the UNESCO World Heritage Site, Landscape of Grand Pré, brings significant numbers of tourists to the province, including members of the wider Acadian diaspora (George 2013). The agricultural products grown on the dykelands are part of a strong local food and drink movement in the province that attracts numerous visitors to the area for an experience that transcends the material, including benefits like social interaction and the consumption of heritage in the form of “terroir” (Winkler et al. 2017). Wildlife observation, particularly bird-watching, is a multi-billion dollar and growing industry in North America (O'Donnell 2016). For birders, locations that offer a mix of habitats (e.g., coastal marsh, forest, freshwater wetlands, fields) tend to allow people to see more types of species. While birding has potential to be a source

of economic development in fine-grained geographies like that of coastal NS (Glowinski 2008), there is a challenge in that birds are often attracted to wetlands but most easily viewed from dykes, which can be eroded through heavy use.

The access benefits that dykes represent along the coast are used by other recreational users (and in some areas, even commuters), including runners, walkers, and cyclists (Chen et al. 2020) as well as motorized users on all-terrain vehicles and dirt bikes and consumptive wildlife users, such as hunters and fishers. Recent work using Instagram to assess nonmaterial benefits in dykelands and tidal wetlands in NS showed that dykes are often used for coastal access (including by school groups) and dykelands are commonly mentioned in photo captions. Consistent with work in North Carolina (Van Berkel et al. 2018), however, the tidal wetland visible in many of the photos is rarely identified as such and thus less clearly understood or valued (Chen et al. 2020). The ES provided by access to natural places, which dyke structures provide in this region, is increasingly recognized as being a key mental, physical, and economic benefit to society (Thompson Coon et al. 2011; Ward Thompson and Aspinall 2011; White et al. 2016). As such, there may be well-being benefits to account for among some individuals and risks in losses of these connections (Cunsolo and Ellis 2018). For others, particularly Mi'kmaq people, the loss of wetlands that help to sustain their livelihoods, cultural practices, and belief systems means the impacts of disconnection are ongoing. It is expected that the boundaries between nonmaterial and other services may be less clear for First Nations people than others, but this is yet to be explored. Such distinctions raise the idea of relational values, which are not entirely instrumental to people (e.g., ES) or intrinsic to an ecosystem, but arise in the interstices of people and nature or between people being together in nature, such as fulfillment from stewardship or shared identity (Chan et al. 2016).

There is much that we do not yet know about the nonmarket, nonmaterial services that dykelands and tidal wetlands might provide and to whom. As difficult as it is to monitor such a diffuse, rural area for its physical uses, it is even harder to understand other values and meanings it might represent. The higher diversity of plant communities found in dykelands may be more aesthetically appreciated by some communities based on visual criteria, including commodities that can generate pleasing linear patterns, such as vineyards and corn. Yet tidal wetlands foster more native plants that may be important to others for food, medicine, or spiritual resources like sweetgrass. The challenge of tracking services becomes even more difficult with the importance of the dykeland system to the identity and culture of the Acadian diaspora (Le Ménestrel 2005; Hodson 2012). A NS survey about dykeland futures was undertaken in 2015, and suggested low attachment to tidal wetlands or their services, but strong attachment to dykelands on the basis of flood protection, food security, recreation, and also for cultural reasons (Sherren et al. 2016). Knowledge gaps abound in all these nonmaterial services and their various sets and scales of beneficiary.

4. Synthesis and conclusions

This baseline exploration of ES delivery by NS dykelands and tidal wetlands reveals broad sets of services (and disservices) and their trade-offs that have been documented in similar landscapes in New England (Taylor 2008) and Europe (Zorrilla-Miras et al. 2014; Karrasch et al. 2019). The overarching theme is one of loss in natural regulating services due to shifts from coastal wetlands to dykelands (Table 1). Trade-offs exist between and within ES categories when considering the specific service (e.g., agriculture versus fisheries) and the beneficiary (e.g., settler versus Mi'kmaq). In a systematic review of over a thousand ES studies from 2000–2013, Howe et al. (2014) established three indications of when trade-offs are likely: (i) private interests in natural resources exist, (ii) provisioning ES are involved, and (iii) local stakeholders are included. The dykeland–wetland challenge includes all three, but transactions associated with dykelands are more likely to be marketized and settler-focused than those associated with wetlands. While the same review indicates that ES trade-offs are three times

more likely to be reported than synergies, the latter win-wins are more likely to be reported when three issues are overcome: (i) failure to account for all benefits/stakeholders, (ii) failed management, and (iii) assumptions that provisioning services should dominate.

The most significant failure thus far has been in understanding how Mi'kmaw people benefit from the dykeland and wetland systems, as well as how they conceptualize and approach the issue of adaptation. This is more complex than it may seem on the surface. Though it has become a cornerstone framework for decision-making, researchers have argued that ES might not capture more intangible or relational values of nature (Chan et al. 2016), such as those held by Indigenous communities (Cooper et al. 2016). Among the studies that consider ES in Indigenous contexts comparable to the dykelands, only a minority have used a classic ES approach by monetizing their findings (Konar et al. 2019; Sangha et al. 2019) and the authors acknowledge that monetization cannot fully capture Indigenous-specific nuance. Most studies use ES as a starting point and adapt it to better align with the Indigenous context. Researchers have approached adaptation by incorporating relational values (e.g., Russell et al. 2020), by emphasizing specific aspects of ES that best reflect the Indigenous community's values (e.g., Robinson et al. 2016), by using theories in addition to ES that foreground the language and experiences of the research participants, or by combining multiple of these approaches (e.g., Satterfield et al. 2013; Levine et al. 2017; Bélisle et al. 2021). Adapting ES to suit the Indigenous research context may better represent and include Indigenous ways of relating to, knowing, and experiencing nature; the importance of such is underscored in the context of reconciliation with Indigenous Peoples over injustices. Such engagement is not only necessary to be a "good" researcher in this context, but also critical to land use change decisions constrained or stimulated by protection of cultural and archeological resources through the NS Special Places Act and Federal Bills C-68 and C-69 that are designed to improve Indigenous engagement and partnership in project reviews and regulatory decisions.

What is suggested here, and described more fully elsewhere (Gómez-Baggethun et al. 2019), is the one-way friction in these landscape changes and the delivery of ES. The conversion from wetland to agriculturally productive dykeland may take a decade, but the trip from dykeland back to fully functioning wetland will be longer. This temporal process is true although *Spartina alterniflora* can come back surprisingly quickly after flow is restored, meaning it looks like a tidal wetland somewhat before it functions like one. Such dynamics are likely characteristic of shifts between regulating and provisioning services. Other evidence suggests, consistent with work elsewhere (Pedersen et al. 2019), that proximity is important for regulating and nonmaterial service delivery, in particular, but poorly understood. This calls for spatial understanding not only of ecosystems but of beneficiaries to understand chaotic and sometimes idiosyncratic flows of ES (Bagstad et al. 2014).

Dykeland decision-making will have to balance the needs of this range and granularity of beneficiaries from individual to group (Scholte et al. 2016), and recognize the possibility of disbenefits as well as benefits (Rendón et al. 2019), ensuring public support (and thus political support) within the context of reconciliation. At the same time, there remain uncertainties in the restoration process itself given global change; past experiences are not always representative of how an ecosystem will react to a management decision today. It is also important to recognize that dykeland services call for more human input than tidal wetlands systems over the long term, so comparisons should be made with caution. In NSERC ResNet, we will help to fill the knowledge gaps identified above about flows of all three categories of final ES from dykelands and both extant and regenerating tidal wetlands to inform decision-making in the complex Bay of Fundy context (Table 2). Integrating such knowledge is the best chance we have at balancing ecosystem delivery across the whole system, and ensuring a healthy, liveable, and sustainable coast.

Table 2. Key knowledge gaps identified and research activities planned under ResNet Landscape 1 Bay of Fundy dykelands.

Identified knowledge gap	Research stream
Wetland vegetation trajectories after restoration	Planting technique experimentation and implications for ecosystem services lag time
Fisheries implications of wetlands	Literature review and experimentation to understand fish use
Storm protection processes and pace in wetlands	Tracking progress of past wetland restorations Quantification of protective services (including resilience to sea-level rise)
Mi'kmaq ecosystem services across categories	Qualitative engagement with Mi'kmaq communities
Net greenhouse gas implications, including non-CO ₂ offsets	Sediment and gas-based greenhouse gas investigation, including mycorrhizal fungi
Non-material services by beneficiaries	Social survey to capture nonmaterial benefits spatially and by beneficiary
Pollination processes in dykelands and wetlands	Pollinator audits across landscape transects
Salt water intrusion with sea level rise	Groundwater monitoring and modelling
Dykeland vegetation trajectories and biodiversity	—

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Author contributions

KS, KE, BK, JL, MLM, DvP, and AKW conceived and designed the study. KS, KE, JAG, BK, NL, JL, MLM, DvP, AKW, TMB, JB, LK, BLTI, and EW drafted or revised the manuscript.

Competing interests

Mark L. Mallory is on the Editorial Board of this journal.

Data availability statement

All relevant data are within the paper and in the Supplementary Material.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:10.1139/facets-2020-0073.

Supplementary Material 1

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