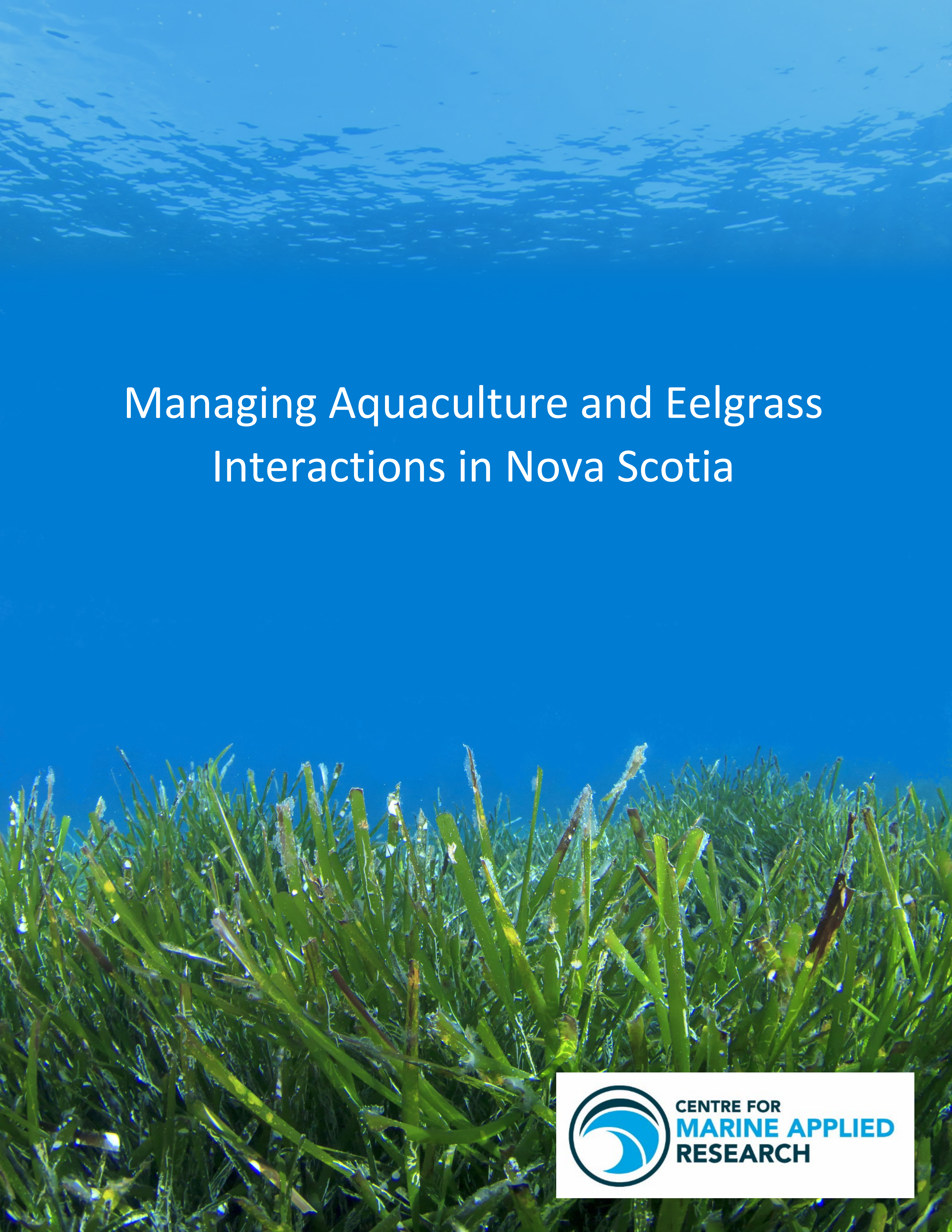

Managing Aquaculture and Eelgrass Interactions in Nova Scotia

CENTRE FOR MARINE APPLIED RESEARCH

Managing aquaculture and eelgrass interactions in Nova Scotia

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Executive summary

Eelgrass (*Zostera marina*) is the primary seagrass species in Atlantic Canada. Eelgrass meadows are ecologically important as they can provide food and habitat to a wide range of birds, fish, and invertebrates. Eelgrass can also enhance sediment stability, improve water clarity, and protect coastlines from erosion. Consequently, eelgrass is an 'Ecologically Significant Species' (ESS) and protected under federal legislation through a prohibition on the harmful alteration, disruption or destruction (HADD) of fish habitat.

Some eelgrass beds in Atlantic Canada have receded in recent years due to a multitude of interacting stressors including disease, species invasions, nutrient enrichment, and climate change. There have been concerns that aquaculture may also have the potential to negatively impact eelgrass, given aquaculture is primarily a coastal activity. This report was written by the Centre for Marine Applied Research (CMAR) to review the potential effects of shellfish and finfish aquaculture on eelgrass beds in Nova Scotia.

Most studies on the impacts of finfish farms on seagrass have examined two species of Neptune grass (*Posidonia oceanica* and *Cymodocea nodosa*) in the Mediterranean Sea. These studies report a general decrease in seagrass cover with increasing proximity to finfish farms for distances up to 300 m, primarily due to the deposition of particulate organic wastes. However, these studies may have limited relevance to finfish aquaculture facilities in Nova Scotia. This is because Mediterranean fish farms are often situated in low nutrient ('oligotrophic'), low energy environments in shallow depths, very close to shore. To date, only one field study has investigated finfish aquaculture and seagrass interactions outside of the Mediterranean, which studied a finfish farm in Port Mouton Bay, Nova Scotia. This study found some evidence of eelgrass cover declining with increasing proximity to the finfish farm, but overall, trends were less clear than those reported in the Mediterranean. Further investigation is warranted as a single field study is insufficient to reach definitive conclusions on finfish aquaculture / seagrass interactions in temperate ecosystems.

In comparison to finfish aquaculture, the potential effects of shellfish aquaculture on eelgrass are better documented. Studies show the primary impact on seagrass is shading from aquaculture gear and infrastructure. Correspondingly, any negative effects are usually highly localized. In general, suspended shellfish aquaculture has less potential to impact eelgrass compared to on-bottom methods.

Managing eelgrass and environmental impact interactions can be difficult as regulators typically have access to very little data on eelgrass, and do not have the resources available to perform detailed surveys on a large scale. However, proposed aquaculture operations must undergo baseline monitoring during which the presence of eelgrass and other fish habitat are assessed by the Federal Government. Mitigation or avoidance measures are then imposed if the operation is considered to pose a risk to fish habitat.

The issue of potential eelgrass / aquaculture interactions has largely been addressed in Eastern New Brunswick due to the adoption of a comprehensive Bay Management Framework (BMF) system for suspended oyster aquaculture. The BMF established a broad range of site selection criteria and operating conditions for the suspended oyster aquaculture industry, which help to ensure oyster aquaculture has minimal impacts on eelgrass without requiring additional data collection. Based on the success of the BMF, a similar management system could be adapted for Nova Scotia. However, the BMF only address the potential impacts of suspended oyster aquaculture. This report proposes several additional measures for other gear types, as well as a consultation process, which could help minimize aquaculture impacts on eelgrass in Nova Scotia.

1. Introduction

1.1. What is seagrass?

Seagrasses are grass-like flowering plants (or 'angiosperms') which grow in areas that are tidally or fully submerged by seawater. They can form dense aggregations known as 'meadows' or 'beds' (Figure 1), and are widely distributed across tropical and temperate coastlines, estuaries and lagoons (Short et al. 2007, Dinusha and Costello 2018). There are around 60 seagrass species worldwide, belonging to 11 different genera and 4 families (Dinusha and Costello 2018). As they have no special morphological or genetic characteristics distinguishing them from other aquatic plants, seagrasses form an ecological group, not a taxonomic group (Tomlinson 1982, den Hartog and Kuo 2006).

Figure 1 | Eelgrass (*Zostera marina*) meadows growing off the coast of Nova Scotia. Source: Fisheries and Oceans Canada (DFO).

1.2. Eelgrass (*Zostera marina*)

There are a total of 11 seagrass genera (reviewed in Jacobs and Les 2009). The genus *Zostera* (family: Zosteraceae) consists of 15 seagrass species. Of these, *Zostera marina* or 'eelgrass' (Figure 1), is the most widespread species in the northern hemisphere of the Pacific and Atlantic Oceans (Green and Short 2003).

1.3. Distribution of eelgrass in Nova Scotia

Eelgrass is the primary seagrass species on the eastern coast of Canada and USA (Fisheries and Oceans Canada 2009). As eelgrass occurs from North Carolina up to northern Quebec, its range includes parts of Hudson Bay, Newfoundland and Labrador, New Brunswick, Prince Edward Island (PEI) and Nova Scotia. In Nova Scotia, eelgrass has been recorded throughout the Northumberland Strait, around Cape Breton, and down to the south shore beyond Yarmouth (Figure 2). As eelgrass does not grow in areas of high energy and turbidity, it tends to be scarcer in the Bay of Fundy (Moore and Short 2006, Fisheries and Oceans Canada 2009, Murphy et al. 2020).

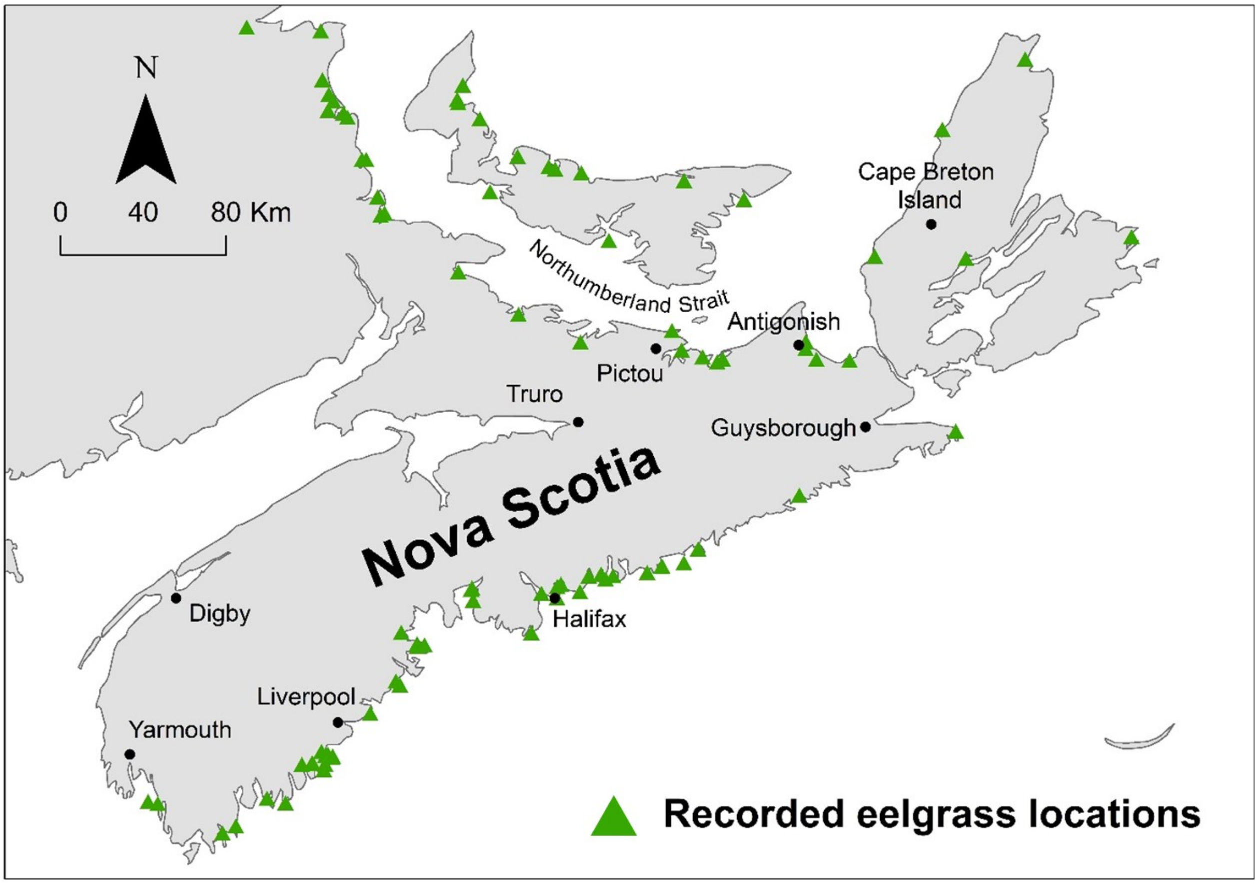

Figure 2 | Locations of recorded eelgrass observations according to data collated by Environment Climate Change Canada (ECCC 2021). These data are not comprehensive and are highly unlikely to reflect the exact present distribution of eelgrass.

Although eelgrass meadows have been reported throughout Nova Scotia and Atlantic Canada, their exact location, density, and overall health are largely unknown. Consequently, Fisheries and Oceans Canada (DFO) have established a 'National Eelgrass TaskForce' (NETForce) which aims to compile all available eelgrass data from across Canada and create a national eelgrass map by April 2022. NETForce are also in the process of satellite mapping eelgrass beds in Nova Scotia (e.g. Wilson et al. 2020) and developing species distribution models (Melisa Wong, DFO, pers. comm. 9th July 2020). DFO's Marine Planning and Conservation unit for the Gulf region are also satellite mapping eelgrass in the Gulf of St Lawrence (Jeffrey Barrell, DFO, pers. comm. 29th September 2020).

1.4. Environmental criteria suitable for eelgrass

There are a wide range of chemical, biological and physical parameters (Table 1) that can influence the distribution of eelgrass (Fisheries and Oceans Canada 2009). There are also many stressors and disturbances that can alter these parameters (see Section 5), which can have significant effects on eelgrass and the ecological communities they support (see Section 3).

Table 1 | Key environmental parameters that can affect eelgrass distribution.

Parameter	Thresholds	References
Ammonium (NH_4^+)	Aquatic toxicity begins at 25 µM and mortality occurs at 125 µM.	van Katwijk et al. (1997)
Current speed	Can tolerate a range of 16 – 180 cm s^{-1}.	Fisheries and Oceans Canada (2009)
Dissolved oxygen (O_2)	Minimum of 2.02 mg O_2 L^{-1} in water.	Fisheries and Oceans Canada (2009)
Hydrogen sulphide (H_2S)	Sediment toxicity begins at 100 µM and mortality occurs at 680 µM.	Fisheries and Oceans Canada (2009), Dooley et al. (2013)
Light	Minimum light requirement: 11 – 34 % surface irradiance (SI) or 1.2 – 12.6 mol photons m^{-2} day^{-1}.	van Katwijk et al. (1997), Hauxwell et al. (2003), Eriander (2017), Bertelli and Unsworth (2018)
Nitrate (NO_3^-)	Aquatic toxicity effects begin at 35 µM and mortality occurs at ~ 250 µM.	Burkholder et al. (1992)
Salinity	Optimal range: 20 – 26 ppt Tolerable range: 5 – 35 ppt	Fisheries and Oceans Canada (2009)
Sediment composition	Reported in sediments ranging in particle size from mud to cobbles.	Fisheries and Oceans Canada (2009)
Redox potential of sediment	Tolerable range for seagrasses in general: -175 to +300 mV.	Marbá et al. (2006)
Water temperature	Optimal range: 10 – 25 °C Tolerable range: 0 – 35 °C	Fisheries and Oceans Canada (2009)
Water depth	The euphotic zone. Maximum of 12 m, but usually occurs between 1 – 7 m.	Moore and Short (2006), (Murphy et al. 2020), Jeffrey Barrell and Melisa Wong (DFO, pers. comm)

2. Eelgrass ecology and life history

2.1. Life history

Eelgrass, like all seagrasses, are clonal plants that grow by replicating modules (or ramets) along their rhizome (Figure 3). These modules consist of: (1) a shoot, which extends into the water column and bears photosynthetic leaves; (2) roots, which anchor the plant in the sediment; and (3) a segment of rhizome, which connects to neighboring modules (Reviewed in Duarte et al. 2006). New modules are formed along the rhizome as it grows and extends horizontally through the sediment, allowing the plant to expand into new areas. Over time, some modules may become physically separated by disturbance events (see Section

5), or through the natural senescence of shoots, resulting in multiple individuals that are all genetically identical. Consequently, although eelgrass meadows appear to consist of many individual plants, they may be connected to the same rhizome, and even if they are not physically connected, they may be genetically identical (Waycott et al. 2006).

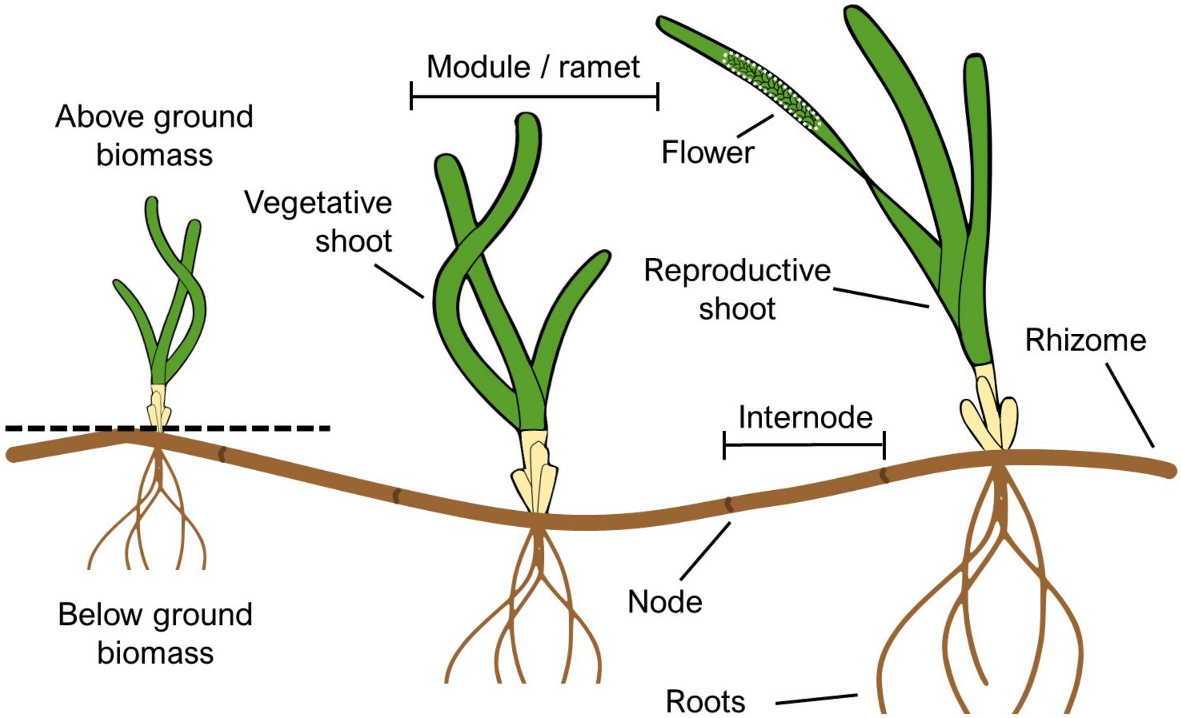

Figure 3 | Key morphological structures of a single eelgrass (*Zostera marina*) plant. Typically, leaves are 20 – 50 cm long but can reach up to 1.5 m; the roots can reach 20 cm in length; the rhizome is 2 – 6 mm thick; and the internodes can range from 5 – 40 mm in length (Borum and Greve 2004, Duarte et al. 2006).

Eelgrass shoots can be vegetative or reproductive. Reproductive shoots are generally taller, more branched, bushier in appearance, and encapsulate male and female flowers along the mid-length of their blades (Tomlinson 1982, Borum and Greve 2004). Male flowers release linear strands of pollen to pollinate the female flowers of neighboring plants. If female flowers become fertilized by the pollen, seeds will form and mature over a period of a few weeks (Figure 4). These seeds are released directly into the water column where they typically become dispersed over 1 – 10 m before settling on the seabed (Reviewed in Marbá et al. 2004). Alternatively, the entire flower or reproductive shoot can break off and float away, dispersing the seeds over a much larger distance (Marbá et al. 2004, Moore and Short 2006). Eelgrass seeds rarely survive longer than a year and may remain dormant within the sediment for up to 6 months before germinating (Coolidge Churchill 1983, Orth et al. 2000). This pool of viable seeds is often referred to as a population's 'seed bank' (Harwell and Orth 2002, Duarte et al. 2006). Sexual reproduction and the resulting seed bank can play an important role in recovery processes because, even if a disturbance destroyed all above and below ground biomass of an eelgrass community (see Section 5), the seed bank may still allow the community to recover in the future (Harwell and Orth 2002).

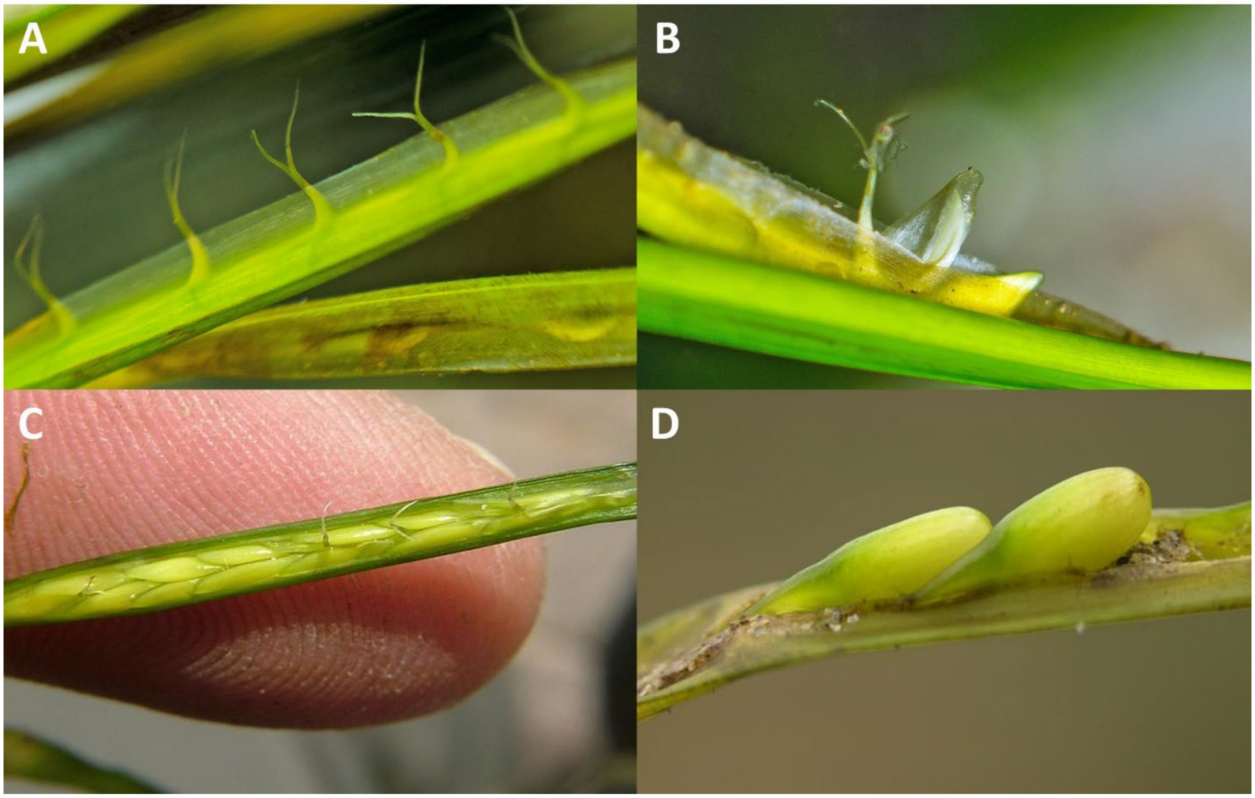

Figure 4 | Reproductive structures of eelgrass: (A) female flower; (B) male flower; (C) developing seeds; (D) seeds ready for dispersal. Source: Images A & B courtesy of Susannah Anderson (https://wanderinweeta.blogspot.com); Images C & D courtesy of David Fenwick Sr (www.aphotomarine.com).

Most seagrasses exhibit very low rates of sexual reproduction and seed production, as the proportion of shoots that flower is usually lower than 10 % (Durako and Moffler 1985, Duarte et al. 1997, Marbà and Walker 1999, Campey et al. 2002). However, sexual reproduction and seed production can exhibit remarkably high levels of spatial and temporal variation (Duarte et al. 2006, van Katwijk et al. 2010). In addition, sexual reproduction has been shown to increase in response to stressors and disturbances, such as fishing disturbance, heat waves, freshwater influxes and storms (reviewed in Cabaço and Santos 2012). Presumably, this is an evolutionary response to promote recovery from the seed bank.

Eelgrass generally has a perennial life history. Under this strategy, plants live for multiple years and reproduction primarily occurs through asexual clonal / vegetative growth (Olesen 1999). However, eelgrass populations employing an annual life history have been reported on several coasts in the Pacific and Atlantic, including in Petpeswick, Nova Scotia (Keddy and Patriquin 1978, Meling-López and Ibarra-Obando 1999, van Katwijk et al. 2010). These annual plants die during the winter but then re-establish from the seed bank, meaning annual plants can complete their life cycle in less than 12 months (Jarvis et al. 2012). In contrast, the seedlings of perennial plants generally require 1 – 2 years before they are able to start flowering (Keddy and Patriquin 1978). Annual populations invest substantially more energy into sexual reproduction than perennial plants, generating an average of 24,000 seeds per square metre compared to 6,200 seeds per square metre in perennial populations (Olesen 1999). The ability for annual populations to die and re-establish from the seed bank is thought to provide a mechanism to mitigate seasonal disturbances such as warm summer temperatures or scouring by sea ice (Keddy and Patriquin 1978, Robertson and Mann 1984, Santamaría-Gallegos et al. 2000). Interestingly, the seeds of perennial plants can give rise to both annual and perennial plants and vice versa (Keddy and Patriquin 1978), and some eelgrass populations are comprised of both annual and perennial plants, known as 'semi-annuals' or 'mixed annuals' (van Katwijk et al. 2010, Jarvis et al. 2012, Vercaemer et al. in press).

Differences in environmental conditions can cause eelgrass morphology to vary within and between populations. For example, the ratio of above ground to below ground biomass can be affected by local hydrodynamic conditions, as eelgrass in high energy environments tend to invest more energy in below ground structures (i.e. roots and rhizomes), presumably to help prevent dislodgement (reviewed in Peralta et al. 2007). Likewise, light limitation can cause eelgrass to display a reduction in below ground biomass and an increase in leaf length and / or shoot density to maximize photosynthetic capability / tissues, and to reduce the amount of stored carbohydrates plants need to allocate to root tissues (Olesen and Sand-Jensen 1993). Overall, a range of biotic (e.g. grazing, and inter- and intra-specific competition) and abiotic (nutrients, temperature and salinity) stressors and disturbances can affect eelgrass morphology and physiology (see Section 5).

2.2. Patch dynamics

Some seagrass populations can form continuous meadows that stretch for hundreds of kilometres (Carruthers et al. 2007), while others may naturally occur as a series of highly fragmented patches (Duarte et al. 2006). Patchy seagrass cover can be the product of colonization processes. For example, new patches can be established by seedlings, or by the dispersal of broken-off shoots which can re-anchor and resume growth in new locations (Marbá et al. 2004). Alternatively, shoot senescence or disturbance events (see Section 5) may cause the loss of some parts of the seagrass meadow, also resulting in fragmented cover (Bell et al. 2006). All these processes can promote the development of a mosaic of patches of different ages and developmental stages (Duarte and Sand-Jensen 1990, Olesen and Sand-Jensen 1994, Vidondo et al. 1997). Consequently, although seagrass meadows appear to be static, they are highly dynamic landscapes in a constant state of contraction, expansion, recruitment, and mortality (Duarte et al. 2006, Marbá et al. 2006, Walker et al. 2006). These high levels of natural variability can complicate monitoring efforts and make it difficult to determine how seagrass meadows respond to disturbance (also see Section 5.7).

2.3. Seasonal fluctuations

Seagrasses can exhibit strong variations in growth, reproduction, and biomass in response to seasonal fluctuations in water temperature and light availability. These fluctuations tend to be more pronounced in temperate and high-latitude seagrass communities as these regions experience stronger seasonal changes in light and temperature than tropical and sub-tropical regions (Duarte et al. 2006).

Generally, eelgrass biomass and shoot density are highest during the summer, when warmer temperatures and greater light availability promote faster rates of growth (Kaldy and Lee 2007). For example, eelgrass beds in Chesapeake Bay (east coast, USA) tend to exhibit greater biomass, leaf length and shoot density between June – July (Orth and Moore 1986). Eelgrass then undergo extensive leaf loss between July – August when water temperatures exceed 25 °C, corresponding with a 200 – 400 % reduction in shoot density and above and below ground biomass. Biomass and shoot density then remain supressed throughout September – April until temperatures begin to rise again during the spring. Chesapeake Bay also exhibits seasonal increases in turbidity which can negatively impact eelgrass recruitment and seedling survival (Moore et al. 1997). Field observations in Nova Scotia, Oregon (west coast, USA), and South Korea also show eelgrass can exhibit fluctuations in growth, biomass, shoot density, and shoot senescence, in response to seasonal changes in light and water temperature (Lee et al. 2005, Kaldy and Lee 2007, Kwak and Huh 2009, Wong et al. 2013). In contrast, several eelgrass beds in Pomquet Harbour and Chezzetcook Inlet, Nova Scotia, display annual fluctuations in biomass due to winter scouring by sea ice (Robertson and Mann 1984, Schneider and Mann 1991). Scouring may be widespread across Nova Scotia as winter ice occurs in potential eelgrass habitat throughout the province (Jeffrey Barrel, DFO, pers. comm. 29th September 2020).

3. The ecological significance of eelgrass

3.1. Sediment stability, biogeochemistry, and water clarity

Seagrasses are often described as "ecosystem engineers" for their ability to modify their physical, chemical, and biological environment (Jones et al. 1997, Bos et al. 2007). For example, as water currents and waves pass over seagrass meadows, some of their energy becomes dissipated. This reduction in water velocity can protect shorelines from coastal erosion and encourages sediment particles suspended in the water to settle on the seafloor (Ondiviela et al. 2014). Seagrasses prevent the resuspension of these sediments by trapping them within their root and rhizome networks (Koch et al. 2006), which can enhance sediment stability, improve water clarity, and allow more light to penetrate to deeper depths (Folkard 2005, Carr et al. 2010).

Seagrass beds can also trap detritus (e.g. dead leaves and rhizomes) and other organic matter, which can act as a carbon store (see Section 3.7). This input of organic matter can greatly boost microbial activity and lead to the formation of distinct bacterial communities compared to surrounding areas (Gacia and Duarte 2001, Marbá et al. 2006, Tarquinio et al. 2019). As bacteria play a fundamental role in ocean biogeochemistry, seagrass meadows can strongly influence the cycling of carbon, nitrogen, sulphur, phosphorus and oxygen (Marbá et al. 2006, Mateo et al. 2006, Romero et al. 2006, Liu et al. 2018).

3.2. Infauna and epifauna

As seagrass beds can improve water clarity, and increase the stability and organic content of sediments, they are often associated with diverse communities of epifauna (i.e. organisms living on seagrass or on the sediment) and benthic infauna (i.e. organisms living within the sediment). Several studies have observed that eelgrass meadows in the Northwest Atlantic support greater diversity and abundance of hydroids, bryozoans, gastropods, polychaetes, amphipods, and other invertebrates compared to non-eelgrass habitats (Orth 1973, Orth 1977, Fisheries and Oceans Canada 2009, Joseph et al. 2012, Wong 2018, Wong and Kay 2019). Likewise, eelgrass beds in Atlantic Canada are often associated with a higher density and greater diversity of seaweeds and epiphytic algae, of which more than 20 species are dependent on eelgrass to complete their lifecycle (Fisheries and Oceans Canada 2009, Schmidt et al. 2012). These organisms can contribute to the food web by providing food to a variety of larger animals including crustaceans, fish, and birds (see Sections 3.3 – 3.9).

3.3. Greater food availability and growth rates

The plant and invertebrate communities associated with seagrass beds can provide food to a wide range of organisms. Correspondingly, eelgrass beds across the Northwest Atlantic coast have been shown to support faster growth rates of juvenile Atlantic cod (*Gadus morhua*), white hake (*Urophycis tenuis*), cunner, (*Tautogolabrus adspersus*), blue crab, (*Callinectes sapidus*) and tautog (*Tautoga onitis*) (Tupper and Boutilier 1995, 1997, Heck et al. 2003, Renkawitz et al. 2011). However, these benefits are not universal as Greenland cod (*Gadus ogac*), winter flounder (*Pseudopleuronectes americanus*) and naked goby (*Gobiosoma bosci*) have been shown to display slower growth rates in eelgrass beds compared to pelagic and unvegetated habitats, suggesting some species may face a trade-off between reduced predation risk (see Section 3.4) and greater food availability (Sogard 1992, Heck et al. 2003, Renkawitz et al. 2011). Likewise, a meta-analysis of over 200 papers showed that other structured habitats, such as macroalgae beds, kelp forest, and oyster and cobble reefs, can benefit juvenile growth rates just as much as seagrass meadows (Heck et al. 2003).

3.4. Predator refuge

Seagrass canopies provide three-dimensional structure to the seabed. In doing so, they can reduce the visual and swimming capabilities of predators, thereby providing a refuge to smaller organisms. For example, aquarium studies have shown predation rates on the daggerblade grass shrimp (*Palaemonetes pugio*) and juvenile Atlantic cod are lower within high densities of artificial eelgrass (Joseph et al. 2012). Similarly, a field study in Newfoundland showed juvenile Atlantic cod experienced lower predation risk in large eelgrass meadows compared to smaller patches and unvegetated areas (Gorman et al. 2009).

3.5. Nursery habitat

By offering greater food availability and protection from predators, seagrass meadows can provide 'nursery habitat' to a wide range of juvenile fish and crustaceans, many of which are of commercial importance (Heck et al. 2003, Bertelli and Unsworth 2014, 2018). Field studies across Atlantic Canada have shown eelgrass beds support higher abundances of juvenile fish including Atlantic cod, cunner, white hake, mummichog (*Fundulus heteroclitus*), Atlantic silversides (*Menidia menidia*), northern pipefish (*Syngnathus fuscus*), as well as fourspine (*Apeltes quadracus*) and threespine (*Gasterosteus aculeatus*) sticklebacks (Gotceitas et al. 1997, Laurel et al. 2003, Joseph et al. 2006, Grant et al. 2007, Renkawitz et al. 2011, Joseph et al. 2012, Schein et al. 2012, McCain et al. 2016). Some of these species (e.g. pipefish and sticklebacks) are known to spawn in eelgrass beds, making them important habitats for their reproduction (Schein et al. 2012).

3.6. Aquatic birds

Eelgrass, and their associated invertebrate and algae communities, form an important dietary component for several migratory birds in Atlantic Canada including American black ducks (*Anas rubripes*), Atlantic brant (*Branta bernicla*), Barrow's goldeneye (*Bucephala islandica*), Canada geese (*Branta canadensis*) and common goldeneye (*Bucephala clangula*) (Hanson 2004a). Of these, Atlantic brant and Canada geese are known to feed almost exclusively on eelgrass shoots (Erskine 1997, Martell 1997, Newman-Smith 1997, Ganter 2000). In some cases, the links between eelgrass meadows and migratory birds are well established. For example, when eelgrass beds in the Antigonish estuary, Nova Scotia, experienced a 95 % loss in below ground biomass between 2000 – 2001 (see Section 5.2), it was immediately followed by a 50 % reduction in goldeneye abundance and the near disappearance of Canada geese from this region (Seymour et al. 2002). Similarly, the dramatic loss of eelgrass from wasting disease in the early 1930's (see Section 5.1) led to the fall migration pattern of Atlantic brant to no longer include a route along the coast of New Brunswick and Nova Scotia (Hanson 2004a). It has therefore been argued that any future declines in eelgrass would have major impacts on waterfowl feeding behaviour, migration patterns and over-winter survival (Seymour et al. 2002, Hanson 2004a, Fisheries and Oceans Canada 2009).

3.7. Blue carbon

Seagrass beds can sequester carbon into underlying sediments by trapping detritus within their rhizome networks. Consequently, seagrass and other forms of 'blue carbon' (e.g. mangroves) could help mitigate the effects of increasing global carbon dioxide levels and climate change (reviewed in Bedulli et al. 2020). However, studies show carbon storage within seagrass beds is highly variable, and in some cases, their carbon storage abilities may be no different than non-seagrass habitats (reviewed in Ricart et al. 2020).

3.8. Trophic subsidies

Seagrass and their associated communities provide energy, or 'trophic subsidy', to a wide range of organisms and ecosystems (see reviews by Mateo et al. 2006, Heck et al. 2008). For instance, seagrass detritus can provide a continual supply of organic matter to deep-sea ecosystems. Likewise, seagrass detritus can wash up on the shore in huge quantities, providing habitat and food to invertebrates, birds, and mammals. Lastly, the high densities of invertebrates and juvenile fish (see Section 3.5) associated with seagrass meadows can disperse into neighbouring habitats and contribute towards commercial fisheries.

4. Legislation regarding eelgrass in Canada

4.1. Ecologically Significant Species (ESS)

DFO designated Eelgrass as an 'Ecologically Significant Species' (ESS) in acknowledgement of its unique influence on the ecology of sand and mud flats in Canada (Fisheries and Oceans Canada 2009). This designation formally recognizes that if "eelgrass were to be perturbed severely, the ecological consequences would be substantially greater than an equal perturbation of most other species associated with this community". Although, ESS designations do not impose legal protection, it is intended to bring attention to species of high ecological significance, in order to promote a greater degree of risk aversion management regarding any human activities that may impact them, or their community properties (Fisheries and Oceans Canada 2007, Coll et al. 2011).

4.2. Marine Protected Areas (MPAs)

Marine Protected Areas (MPAs) aim to protect organisms and their habitats by partially or fully restricting human impacts within their boundaries. There are currently no MPAs in Atlantic Canada which specifically protect eelgrass beds as part of their management objectives. However, the Basin Head MPA, located on the eastern shore of PEI, encompasses some patches of eelgrass (Fisheries and Oceans Canada 2016a, b). Most of this eelgrass occurs within Zone 2 (Figure 5), which is less protected than Zone 1, as it permits small levels of oyster harvesting within its boundaries. Nonetheless, there are some general signs of eelgrass recovery within the MPA (Jeffrey Barrell, DFO, pers. comm. 16th July 2020).

The Eastern Shore Islands are located on the eastern shore of Nova Scotia and have recently been selected as an Area of Interest (AOI) by DFO (Fisheries and Oceans Canada 2020d). This 2,000 km^2 region (Figure 6) contains over 340 km^2 of eelgrass in its near-shore coastal areas (Wilson et al. 2020). If approved, the Eastern

Shore Islands AOI would be the first MPA in Atlantic Canada that officially lists the protection of eelgrass habitats as one of its management objectives (Tanya Koropatnick, DFO, pers. Comm, February 2021).

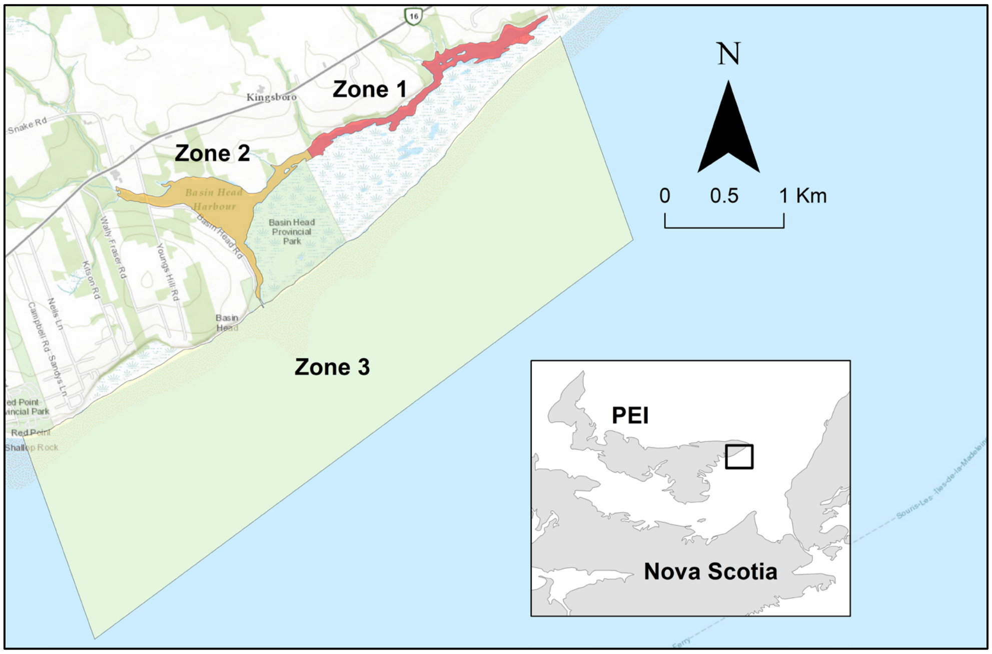

Figure 5 | The Boundaries of the Basin Head MPA. Zone 1 is the most protected part of the MPA and Zone 3 is the least protected. Inset shows the location of the MPA in relation to Prince Edward Island (PEI) and Nova Scotia. Source: Government of Canada (2020g).

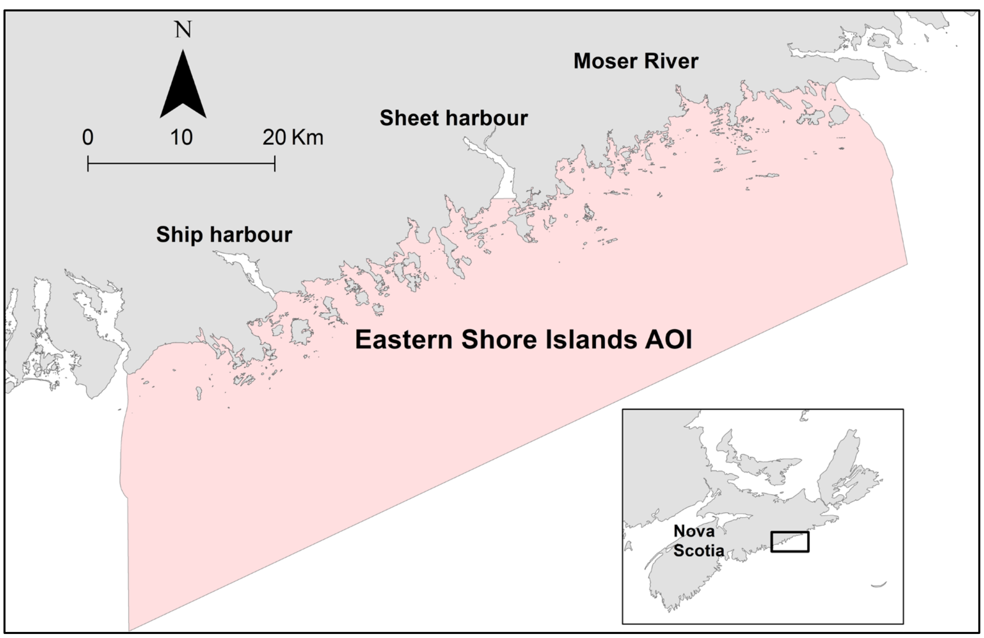

Figure 6 | The boundaries of the Eastern Shore Islands AOI located along the eastern shore of Nova Scotia. This area is under review for MPA designation, and if approved, would include the protection of eelgrass as one of its management objectives. Source: DFO.

4.3. Other spatial management areas

In addition to MPAs, other spatial management areas are likely to encompass eelgrass meadows in Atlantic Canada. For example, there are eelgrass beds in the Little Port Joli Estuary, located within Kejimkujik National Park Seaside Adjunct (Government of Canada 2020f). However, disturbance from invasive European green crabs (*Carcinus maenas*; see Section 5.2) have caused these eelgrass beds to decline by 98 % (Parks Canada 2016). Kouchibouguac National Park in New Brunswick also encompasses extensive eelgrass beds (Joseph et al. 2006). Lastly, several National Wildlife Areas (e.g. Boot Island) in Nova Scotia are likely to encompass eelgrass (Jeffrey Barrell, DFO, pers. comm. 16th July 2020) and some Migratory Bird Sanctuaries (e.g. Port Joli, Port l'Hebert, and Sable River) were designated partly because migratory geese feed on eelgrass in these areas (Melisa Wong, DFO, pers. comm, February 2021). Migratory Bird Sanctuaries and National Wildlife Areas are managed by the Canadian Wildlife Service (CWS), part of Environment Climate Change Canada (ECCC). For a full list of these sites, see:

- www.canada.ca/en/environment-climate-change/services/national-wildlife-areas.html and;
- www.canada.ca/en/environment-climate-change/services/migratory-bird-sanctuaries.html

4.4. Species at Risk Act (SARA)

The federal *Species at Risk Act* (SARA; S.C., 2002) aims to:

- Prevent the extinction of wildlife in Canada;
- Help the recovery of species that are 'Threatened', 'Endangered' or 'Extirpated' (i.e. a species that no longer exists in the wild in Canada but does elsewhere); and
- Prevent species of 'Special Concern' from becoming Threatened or Endangered (Government of Canada 2020e).

Under SARA, any actions that could harm or harass species on Schedule 1 of the List of Wildlife Species at Risk are legally prohibited within Canada (Government of Canada 2020h). The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) are an independent panel of experts and are responsible for assessing the status of wildlife species and, if necessary, for recommending classifications that impose their legal protection. COSEWIC are also responsible for identifying 'critical habitats' that are key to the conservation of Schedule 1 species, and for developing plans and strategies (e.g. voluntary actions, stewardship measures, and legal action if necessary) to prevent their harm and destruction.

At present, eelgrass is not a Schedule 1 species, nor is it considered to be 'Threatened', 'Endangered', or of 'Special Concern', nor is it a 'Critical Habitat' of any other Schedule 1 species. However, there are several COSEWIC-assessed species that are closely associated with eelgrass meadows in Atlantic Canada, which are reviewed in the following sections:

4.4.1. Barrow's goldeneye

The eastern population of Barrow's goldeneye is designated 'Special Concern' on Schedule 1 of the List of Wildlife Species at Risk (Government of Canada 2020c). A very small proportion (approximately 400 individuals) of this population overwinter in Maine and Atlantic Canada. Barrow's goldeneye have been reported to use estuaries containing eelgrass in Atlantic Canada (Hanson 2004a).

4.4.2. American eel

The American eel (*Anguilla rostrata*) is considered to be 'Threatened' by COSEWIC and consultations are currently underway to determine if it should be listed on Schedule 1 of the List of Wildlife Species at Risk (Government of Canada 2020a). Evidence from Chesapeake Bay suggest American eels may inhabit eelgrass meadows (Orth and Heck 1980) and a DFO report states that eelgrass meadows in Atlantic Canada are "frequently used as habitat of eels in estuaries" (Chaput et al. 2013). However, there is currently no direct evidence that American eels are dependent on eelgrass meadows in Atlantic Canada.

4.4.3. Atlantic cod

Under SARA, Atlantic cod are divided into four discrete populations: the Maritimes populations (divided into the Laurentian South and the Laurentian North populations); the Newfoundland and Labrador population; and the Arctic population. Except for the Arctic population, all are considered to be 'Endangered' by COSEWIC but are not listed on Schedule 1 of the List of Wildlife Species at Risk (Government of Canada 2020b). As previously discussed (see Section 3.5), eelgrass beds provide important nursery habitats to juvenile cod in Newfoundland and Labrador, and to a lesser extent, in Nova Scotia (Melisa Wong, pers comm, 16th July 2020).

4.4.4. Atlantic salmon

In Nova Scotia, wild Atlantic salmon (*Salmo salar*) are divided into four discrete populations: Inner Bay of Fundy; Southern Upland; Eastern Cape Breton; and the Gulf of St Lawrence. Except for the Gulf of St Lawrence, all are considered to be 'Endangered' by COSEWIC but only the Inner Bay of Fundy population is listed on Schedule 1 of the List of Wildlife Species at Risk (Fisheries and Oceans Canada 2020c). There is no direct evidence that Atlantic salmon use eelgrass meadows in Nova Scotia, but they are thought to use eelgrass beds in the Gulf of St. Lawrence, and in Newfoundland and Labrador (Heike Lotze, Dalhousie University, pers. comm. 20th July 2020). The general lack of evidence is believed to be a result of their low abundance, which would reduce the probability of salmon appearing in dive and video surveys of eelgrass meadows. It is probable that their historic migration routes overlapped with eelgrass meadows in Nova Scotia (Heike Lotze, Dalhousie University, pers. comm. 20th July 2020).

4.4.5. Eelgrass limpet

The eelgrass limpet (*Lottia alveus*) is considered to be 'Extinct' by COSEWIC (Government of Canada 2020d). This mollusc fed exclusively on the epithelial tissues (i.e. the outer-most layer) of eelgrass and was once distributed throughout the Northwest Atlantic coast. The large outbreak of wasting disease during the 1930's caused an unprecedented decline in eelgrass cover (see Section 5.1), and led to the extinction of this species.

4.5. The Fisheries Act and HADD provisions

Section 35 of the *Fisheries Act* (R.S.C. 1985) legally prohibits the "harmful alteration, disruption or destruction" (HADD) of eelgrass and other fish habitat. This means that if a proponent damages fish habitat, they could be prosecuted for breaching federal law. However, exceptions are granted to works, undertakings or activities that may cause a HADD if they are 'prescribed' or belong to a 'prescribed class', or if authorization is granted from a federal authority following an environmental assessment (Fisheries and Oceans Canada 2020f). To gain authorization, the proponent must demonstrate how they intend to minimize habitat impacts, and the authorization will usually impose responsibilities for mitigation, habitat restoration or offsetting, and monitoring. This legislation has important implications for a variety of activities, including aquaculture (see Section 8 on aquaculture and eelgrass management).

The concept of HADD has a long and complex history. The *Fisheries Act* first came into force in 1868 and outlined a series of legal measures aimed at conserving and protecting fish and their associated habitats (Fisheries and Oceans Canada 1995). HADD was then introduced to the *Fisheries Act* in 1977 to strengthen protection of fish and their habitats. In 2012, the *Fisheries Act* was revised and HADD was removed and replaced with a prohibition on works, undertakings or activities that result in "serious harm to fish that are part of a commercial, recreational or Aboriginal fishery", commonly referred to as CRA. Scientists, environmental groups, and other stakeholders expressed concerns that these amendments could lessen the protection afforded to wildlife as the change from "harmful alteration, disruption or destruction" to "serious harm" might permit greater levels of environmental damage, and that only species targeted by fisheries were protected, rather than all species (Wilt 2018). In response, the Federal Government led a review in 2016 and HADD was reintroduced to the *Fisheries Act* in 2019.

To help assist federal and provincial regulators determine what may constitute a HADD to eelgrass, DFO held a science peer-review meeting in 2011 (Fisheries and Oceans Canada 2012) and proposed the following interpretations:

- **No effect:** Eelgrass bed integrity is not compromised. No observable changes in eelgrass structure, within natural variation. Fish habitat function is unaffected or improved.
- **Disruption:** Eelgrass beds will recover their structure and integrity within one year. Patchiness is increased only to the point that recolonization of bare areas, increased density, or return to original meadow size can occur within one year.
- **Harmful alteration:** After a year or more, eelgrass beds will only recover part of their structure and integrity. Patchiness is permanent (relative size of corridors to patches), shoot density will remain low, meadow size is reduced for more than one year.
- **Destruction:** Eelgrass meadow will not survive beyond the season and will not recover without intervention.

The reviewers also identified five key stressors that could cause a HADD to eelgrass (see Section 5 for greater detail on stressors to eelgrass):

1. **Sedimentation:** which may cause burial of eelgrass.
2. **Light limitation:** which may reduce eelgrass growth and lead to mortality.
3. **Nutrient loading:** which may lead to anoxia, nitrogen toxicity, and sulphide accumulation.
4. **Water flow:** Which controls sediment erosion and eelgrass distribution.
5. **Physical damage:** Which can cause immediate rhizome / shoot damage.

Thresholds were proposed for some of these stressors but the peer-reviewers acknowledged that these are largely unrealistic because: (1) eelgrass stressors rarely act in isolation and little is known about their interactive and cumulative effects (see Section 5.7); (2) stressors act on eelgrass against a background of high natural variability (see Section 2); (3) eelgrass recovery is highly variable and depends on the strength of the seed bank and connectivity to nearby patches (see Section 2); and (4) that most scientific evidence for these thresholds come from highly controlled, short-term laboratory studies that do not reflect long-term eelgrass dynamics under real world conditions (see Section 5). Consequently, this remains an active area of research and policy development (Jeffrey Barrell, DFO, pers. comm. 21st July 2020).

5. Eelgrass declines in Nova Scotia

Some eelgrass beds in Atlantic Canada have declined in recent years (Garbary and Munro 2004, Malyshev and Quijón 2011, Murphy et al. 2020). Anecdotal reports and scientific observations suggest that eelgrass meadows occupied most suitable intertidal mud flat areas in Nova Scotia until the late 1970's (Sharp and Semple 2004). However, by the early 1990's to 2000's, many of these areas had little to no eelgrass cover (Seymour et al. 2002, Chapman and Smith 2004, Sharp and Semple 2004, Garbary et al. 2014). The declines within Antigonish estuary (see Section 5.2) are perhaps the most dramatic and well documented, as eelgrass meadows in this area experienced a 95 % reduction in biomass between 2000 – 2001 (Seymour et al. 2002, Garbary et al. 2014). Similar declines have been reported in Petpeswick, which underwent a 96 % reduction in eelgrass cover between 1992 – 2002, while eelgrass beds in Cole Harbour declined by just 49 % during the same time period (Chapman and Smith 2004). On a longer time-scale, eelgrass beds in Lobster Bay underwent a 30 – 44 % reduction in eelgrass cover between 1978 – 2000 (Sharp and Semple 2004).

To discuss the possible drivers underlying these declines, and the issues surrounding eelgrass mapping and monitoring, a technical workshop (attended by over 40 experts) was held in New Brunswick in 2003 (Hanson 2004b). It was concluded that no single casual factor was likely to be responsible. Rather, a multitude of interacting factors were likely causing eelgrass declines in Nova Scotia, as detailed in the following sections.

5.1. Wasting disease

In the early 1930's, eelgrass populations across the Atlantic coasts of North America and Europe were decimated by an outbreak of 'wasting disease' (Muehlstein 1989). This disease is caused by an infectious slime mold (*Labyrinthula zostera*) that spreads via direct leaf-to-leaf contact and causes eelgrass shoots to develop black-brown dots and streaks, eventually leading to their mortality. It is thought that the outbreak in North America started in Virginia in 1930, which spread northwards to Eastern Canada. By 1931, more than 90 % of eelgrass beds had disappeared along the Northwest Atlantic coast, rising to 99 % the following year. Although recovery was relatively slow, many eelgrass beds had re-established by the early 1950's. A recurrence of the disease was documented across New England in 1984, and led to significant declines of up to 80 % in some populations (Short et al. 1988).

Wasting disease continues to affect eelgrass beds in North America and Europe with variable degrees of loss (Garbary and Munro 2004, Moore and Short 2006) and can be detected at low levels in eelgrass beds throughout Atlantic Canada (Jeffrey Barrell, DFO, pers. comm. 29th September 2020). The general consensus is that the disease is not responsible for the present-day declines in eelgrass in Atlantic Canada (Garbary and Munro 2004, Garbary et al. 2014), although it could potentially be an important factor in populations subject to multiple stressors (see Section 5.7).

5.2. Invasive European green crab

The European green crab (Figure 7) is native to coastal waters in the Northeast Atlantic, and the Baltic and North Seas, with its distribution traditionally ranging from Norway to Northwest Africa (Grosholz and Ruiz 1996). However, new populations have established along the Pacific and Atlantic coasts of North America, as well as in South Africa, Australia, and New Zealand. Consequently, the European green crab is considered to be one of the world's most invasive species (Fisheries and Oceans Canada 2020e). It was first detected in North America during the early 1800s in New England (Carlton and Cohen 2003, Matheson et al. 2016). The population then expanded into the Bay of Fundy during the 1950's. By 2007, sightings of European green crab had been reported all across Atlantic Canada, from Nova Scotia to the southern shore of Newfoundland (Fisheries and Oceans Canada 2020e).

Figure 7 | A European green crab (*Carcinus maenas*) inhabiting an eelgrass meadow in Kejimkujik National Park Seaside. Source: Parks Canada.

The European green crab is a highly aggressive and voracious predator that can outcompete native species for food. In Atlantic Canada, it can prey on a variety of intertidal organisms including oysters, mussels, clams, and native crab species (Grosholz and Ruiz 1996, Klassen and Locke 2007, Fisheries and Oceans Canada 2020e). It can also damage eelgrass by feeding on the base of their shoots (Malyshev and Quijón 2011) and by uprooting their roots and rhizomes while digging for clams and other invertebrates buried within the sediment (Seymour et al. 2002, Garbary and Munro 2004). Evidence from a field enclosure experiment in Tracadie Harbour, Nova Scotia, suggested that European green crabs within the harbour can remove up to 87,000 eelgrass shoots (~ 890 kg) per day (Garbary and Munro 2004).

In Nova Scotia, damage from European green crabs is thought to be the primary mechanism responsible for a 95 % reduction in eelgrass cover in Antigonish between 2000 – 2001, as European green crabs had reached an abundance of 385,000 individuals per km^2 during this time (Campbell 2001, Seymour et al. 2002). This notion was reinforced after surveys in 2013 observed European green crabs had reduced to < 1 individual per km^2, and eelgrass cover had recovered to 60 % of its pre-2000 values (Garbary et al. 2014). European green crabs are also thought to be partly responsible for a 98 % reduction in eelgrass cover in Kejimkujik National Park Seaside between 1987 – 2010 (Parks Canada 2016). Lastly, a survey of 13 estuaries in New Brunswick, PEI and Nova Scotia between 2001 – 2002, found eelgrass biomass was generally lower in estuaries invaded by European green crab, compared to uninvaded ones (Locke and Hanson 2004).

5.3. Reduced light availability

Seagrasses, like all plants, require light to photosynthesize sugars and other carbohydrates necessary for respiration and growth. Consequently, light availability is one of the most important factors controlling seagrass growth (Dennison and Alberte 1985, Duarte et al. 2006, Schmidt et al. 2012). There are many natural and human sources of disturbance that can reduce light availability and impact seagrasses, including sedimentation and sediment resuspension from storms, river discharge, coastal construction, moorings and dredging (see Section 5.6). Shading from marinas and aquaculture infrastructure (see Section 7) can also reduce the amount of light available to seagrass, as can eutrophication, which can cause excessive phytoplankton and epiphyte growth (see Section 5.4). Conversely, there is some evidence that suspended oyster aquaculture can increase eelgrass growth by improving water clarity, reducing epiphyte loads, and providing more nutrients to eelgrass (see Section 7.4.1)

Burke et al. (1996) conducted several experimental field manipulations in Virginia, USA, and reported that shading eelgrass for three weeks led to reductions of 40 – 51 % in tissue sugar concentration, 34 % in leaf biomass, 27 % in shoot density, and 23 % in root and rhizome biomass. Similar field manipulations have been conducted in Nova Scotia and have yielded similar results (Wong et al. 2020). Such negative responses tend to get stronger with longer durations of light reduction (Ralph et al. 2006). For example, a laboratory study conducted by Bertelli and Unsworth (2018) demonstrated that reducing light levels below 20 µmol photons $m^{-2} s^{-1}$ resulted in significant reductions in eelgrass growth and photosynthetic performance after 7 days, a 41 % reduction in leaf size after 29 days, and shoot mortality within 4 – 6 weeks (Bertelli and Unsworth 2018). Burial under sediments can also affect seagrass by reducing the area of the plant available for photosynthesis. For instance, a field manipulation study by Mills and Fonseca (2003) showed that eelgrass buried up to 25 % of their height for 24 – 28 days resulted in a 75 % mortality rate, which increased to 100 % between burial depths of 50 – 75 % (Mills and Fonseca 2003). Thus, it was concluded that eelgrass has a particularly low threshold for tolerating burial.

5.4. Nutrient enrichment and eutrophication

Nutrient concentrations can become elevated in coastal waters, rivers and estuaries due to the release of effluents from agriculture, aquaculture (see Section 7), industrialization, urbanization, wastewater treatment plants, and other human activities (Nixon 1995, Smith 2003).

Elevated nutrient concentrations can reduce light levels by promoting the growth of: (1) phytoplankton, which can reduce water clarity; (2) benthic macroalgae, which can compete with seagrasses for light and space; and (3) epiphytic algae and other organisms which grow on the blades of seagrass, obstructing them from light (Williams and Ruckelshaus 1993, Short et al. 1995, Hauxwell et al. 2001, McGlathery 2001, Hauxwell et al. 2003). A survey of 12 estuaries in PEI and New Brunswick between 2007 – 2008 showed that those with elevated nutrient levels supported almost double the biomass of phytoplankton, 40 times more epiphytic algae, and 670 times more opportunistic green macroalgae (Schmidt et al. 2012). Due to restricted light availability, the eelgrass growing in these nutrient enriched estuaries exhibited significantly lower shoot density, as well as lower above and below ground biomass (Schmidt et al. 2017).

As well as restricting sunlight, high biomasses of phytoplankton and macroalgae can cause greater quantities of detritus and organic matter to settle and decompose on the seafloor. In oxygenated environments, bacteria decompose this organic matter through aerobic respiration, consuming oxygen in the process. However, excessive quantities of organic matter can cause bacteria to partially ('hypoxia') or fully ('anoxia') deplete oxygen, prompting bacteria to switch to anaerobic respiration, which can cause hydrogen sulphide (H_2S) and other sulphide compounds to build-up within the sediment (Bricker et al. 2007, Schmidt et al. 2012, Benson et al. 2013). Eelgrass is relatively tolerant to anoxia compared with other seagrass species, but low oxygen levels can reduce its metabolism and growth (Pregnall et al. 1984, Smith et al. 1988). Sulphides are potentially a bigger threat as they are toxic to seagrasses and have been shown to significantly affect eelgrass photosynthesis, metabolism, leaf size, and shoot height, which can lead to their mortality (Carlson et al. 1994, Goodman et al. 1995, Terrados et al. 1999, Pedersen et al. 2004). For example, Dooley et al. (2013) observed that eelgrass seedlings were consistently killed when exposed to water H_2S concentrations above 680 µM. The degree to which sulphides impact eelgrass is strongly linked to oxygen concentrations both within the water column and sediment, as eelgrass can resist sulphides from entering their tissues provided their roots and rhizomes are supplied with sufficient levels of oxygen (Pedersen et al. 2004).

Another potential impact of nutrient enrichment is nitrogen toxicity. Effluents from human activities can release nitrate (NO_3^-) and ammonium (NH_4^+) into coastal waters, which can be toxic to seagrasses when present in high concentrations. Burkholder et al. (1992) maintained eelgrass in elevated water NO_3^- concentrations of approximately 200 ~ 300 µM for 8 weeks, and found that it caused their shoots to crumble, which eventually led to their mortality (Moore and Wetzel 2000). Likewise, van Katwijk et al. (1997) observed that water NH_4^+ concentrations of 25 µM adversely affected eelgrass, and that concentrations of 125 µM led to their mortality within 2 – 5 weeks. Interestingly, seagrasses are more tolerant to high nitrogen concentrations within the sediment than in the water column. For instance, Peralta et al. (2003) demonstrated that eelgrass could tolerate sediment NH_4^+ concentrations up to 30 mM, which is 1200 times higher than what they can tolerate in the water (van Katwijk et al. 1997). Nitrogen toxicity also depends on sediment type, as eelgrass has been shown to be less sensitive to NH_4^+ when growing in muddy sediments compared to sand (van Katwijk et al. 1997).

Overall, the process of nutrient enrichment leading to hypoxia and increased algal biomass, known as 'eutrophication', is considered to be one of the most important drivers underlying the loss of seagrass worldwide (Kenworthy et al. 2006, Walker et al. 2006). However, the effects of nutrient enrichment and eutrophication on seagrasses are highly complex, and can be strongly influenced by a range of other factors including sediment composition, light availability, temperature, oxygen concentration and sediment redox potential (McGlathery 2001, Walker et al. 2006).

5.5. Warming temperatures and increasing storms

Ocean temperatures have displayed general warming trends over the last three decades in the Bay of Fundy, Scotian Shelf, Cabot Strait, Northumberland Strait, and Gulf of St Lawrence. Since records first began in

1985, three of the five warmest years have occurred in 2012, 2014, and 2015 (Herbert and Pettipas 2016, Bernier et al. 2019). However, some parts of the Bay of Fundy and Halifax Harbour have exhibited a general decrease in temperature, or no significant change in temperature (Herbert and Pettipas 2016). Nonetheless, ocean temperatures in Canada are projected to continue increasing over the 21st century, and the waters in Southern Atlantic Canada (Figure 1) are expected to warm faster than the rest of the country (Greenan et al. 2019, Lavoie et al. 2020). Overall, predictions under a high emissions scenario suggest summer sea surface temperatures may increase by 4 °C by 2050 in Atlantic Canada (Greenan et al. 2019).

Eelgrass is widely distributed across the sub-Arctic, temperate and sub-tropical regions of the Pacific and Atlantic Oceans, indicating that it can tolerate a wide a range of temperatures. However, the rate at which ocean temperatures are rising, coupled with an increasing occurrence of unusually warm and long summer temperatures (Greenan et al. 2019), could pose a threat to eelgrass meadows in Atlantic Canada. A laboratory study by Nejrup and Pedersen (2008) found that eelgrass collected from Danish estuaries experienced a 12-fold increase in shoot mortality when exposed to temperatures of 25 – 30 °C compared to 10 – 20 °C. Temperature studies are often confounded by oxygen concentrations, since warmer waters inherently contain less oxygen. Hammer et al. (2018) avoided this issue by exposing eelgrass collected from Virginia, USA, to elevated temperatures, while maintaining oxygen saturation at 100 %. Their study determined that temperatures of 26 °C and 30 °C negatively affected leaf growth, leaf formation, rhizome growth, root formation, and survival compared to eelgrass incubated at 22 °C. These negative relationships could explain why Reusch et al. (2005) lost half of their experimental eelgrass plots in the Baltic Sea after a summer heatwave caused water temperatures to exceed 25 °C. These effects may also partly explain why Wong et al. (2013) observed lower biomass, production and growth of Nova Scotian eelgrass beds in Kejimkujik compared to Port Joli and Port L'Hebert, as water temperature temperatures were higher in Kejimkujik. Paradoxically, increases in eelgrass cover have been reported for most of Newfoundland, possibly due to warmer temperatures reducing scouring by sea ice (Bernier et al. 2019).

Sea levels, and the frequency of flooding and storm events, are also projected to increase with rising temperatures in Atlantic Canada (reviewed in Atkinson et al. 2016, Lemmen et al. 2016, Rapaport et al. 2017). These changes could increase the susceptibility of eelgrass to erosion, dislodgement, sediment burial, and turbidity and salinity changes, which could lead to a general alteration in habitat suitability of existing eelgrass locations (reviewed in Perry et al. 2019).

5.6. Mechanical damage

Seagrasses are generally restricted to shallow areas that are sheltered from large waves and strong winds. These sheltered locations are also attractive areas for the anchoring and mooring of boats. Tides and winds cause boats to rotate around a central anchor point, causing their mooring chains to drag across the seafloor over a fixed radius (Hastings et al. 1995). This can cause repeated physical disturbance to any underlying seagrass (Figure 8) by tearing shoots and uprooting rhizomes (Bourque et al. 2015, Glasby and West 2018). A study in the south-west of England documented that each individual boat mooring resulted in the loss of over 120 m^2 of eelgrass (Unsworth et al. 2017). Dragging of anchors and mooring chains can also resuspend sediments and increase the risk of burial (Unsworth et al. 2017, Glasby and West 2018). There are many 'seagrass friendly' mooring designs available to boaters that reduce damage to seagrass, and several scientists have argued that their use should be legally imposed by legislation (e.g. Demers et al. 2013, Luff et al. 2019).

Figure 8 | Photo of Lake Macquarie in New South Wales, Australia. Each boat mooring has removed a clear radius of seagrass from the seabed. Source: Dr Tim Glasby.

Motorboats can also cause 'propeller scars' by removing and damaging seagrass leaves, shoots and rhizomes (Zieman 1976, Dawes et al. 1997). Such scars are extensive across Atlantic Canada (Jeffrey Barrell, DFO, pers. comm. 29th September 2020). Finally, coastal construction, dredging, and fishing activities (e.g. scallop dredging and oyster tonging) can damage seagrass shoots and reduce their growth through sediment resuspension (Fonseca et al. 1984, Short and Wyllie-Echeverria 1996, Erftemeijer and Robin Lewis 2006, Nordlund et al. 2018).

5.7. Multiple stressors and their interactive effects

The previous sections of this report describe how seagrasses can be affected by a wide range of natural and anthropogenic stressors. However, it is very rare for stressors to occur in isolation. For instance, Murphy et al. (2019) developed a metric to assess the cumulative impact of multiple human activities on seagrass. By applying this metric to 180 eelgrass beds in Atlantic Canada, they found eelgrass existed across a wide spectrum of human impacts including nutrient enrichment, species invasions, fishing, aquaculture, and coastal construction. A growing number of studies show that multiple stressors can interact, and the effects of one can cause seagrass to become more sensitive to another (Blake and Duffy 2012, Brown et al. 2014, Stockbridge et al. 2020, Vieira et al. 2020, Krumhansl et al. 2021). Conversely, some stressors have been shown to have no interactive effects, while others can reduce the sensitivity of seagrass to other stressors (Blake and Duffy 2010, York et al. 2013, Mvungi and Pillay 2019). Consequently, it is difficult to isolate or predict the effects of a single stressor on seagrass populations in a field-based setting, especially considering their spatial dynamics and annual and seasonal fluctuations (see Section 2).

5.8. Aquaculture

Aquaculture describes the culture of aquatic plants (e.g. seaweeds and algae) and animals (e.g. finfish and shellfish) grown in the sea, areas of freshwater, or in tanks on land. As the majority of aquaculture in Atlantic Canada (see Section 6.1) occurs within coastal waters, it has potential to coincide and interact with eelgrass meadows. The remainder of this report focuses on these potential interactions.

6. Aquaculture in Atlantic Canada

The aquaculture industry in Atlantic Canada has exhibited significant growth since the mid-1980's (Figure 9). New Brunswick is the largest aquaculture producer, followed by PEI, Newfoundland and Labrador, and finally by Nova Scotia. Finfish represent over 80 % of all aquaculture production in the Maritimes, except in PEI where production is almost exclusively focused on shellfish.

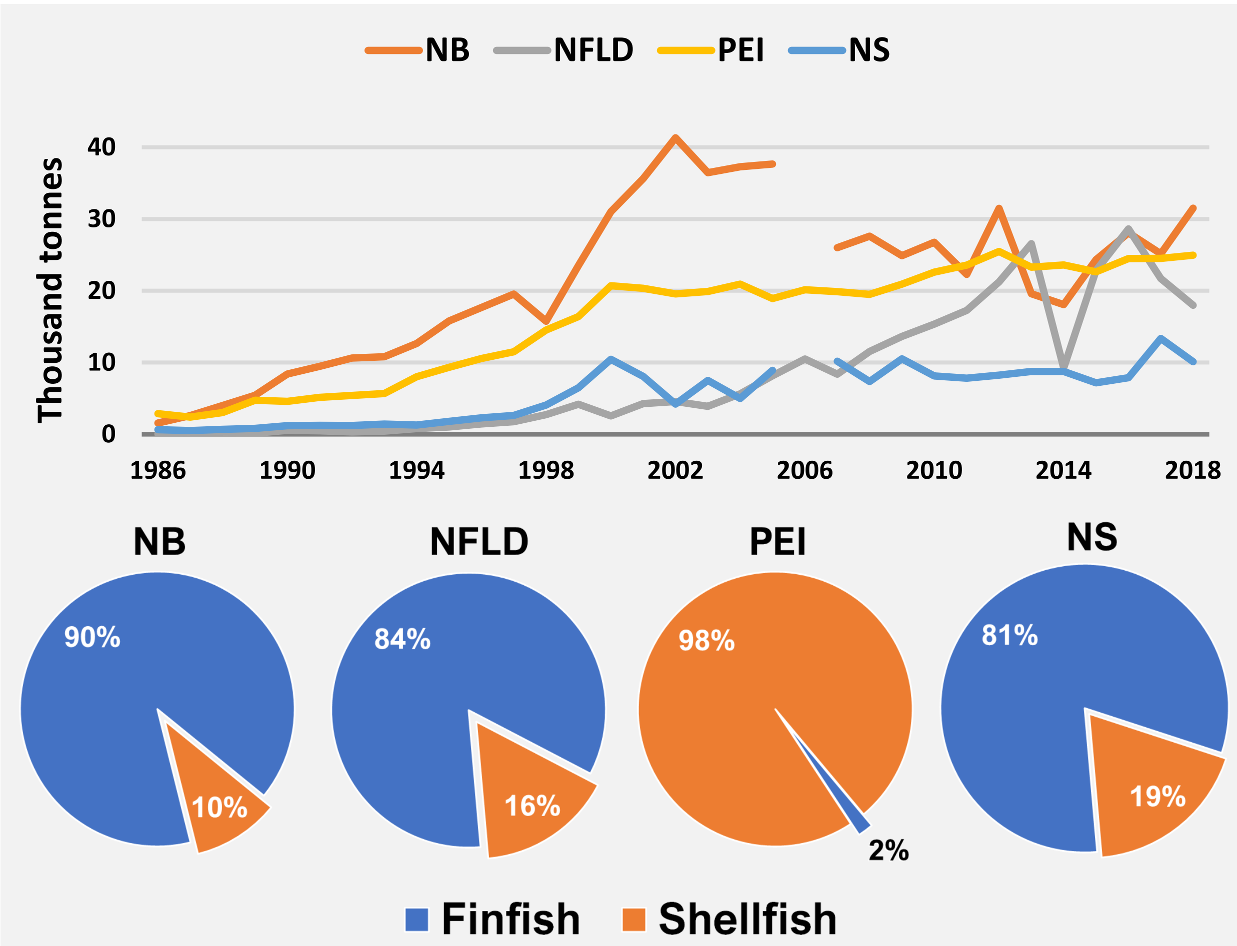

Figure 9 | Annual levels of aquaculture production in the Maritime provinces (top) and the proportion of production in 2018 dedicated to finfish and shellfish (bottom). NB = New Brunswick, NFLD = Newfoundland and Labrador, PEI = Prince Edward Island, and NS = Nova Scotia. Source: Fisheries and Oceans Canada (2020b). Gaps represent years with no available data.

6.1. Aquaculture in Nova Scotia

The aquaculture industry in Nova Scotia has seen substantial growth since the early 1990's, with production increasing five-fold since 1995 (Figure 10). This growth is mostly due to the expansion of the Atlantic salmon industry, and to a much lesser extent, for steelhead / rainbow trout (*Oncorhynchus mykiss*). Consequently, finfish aquaculture now represents 81 % of all aquaculture production by weight (8,201 tonnes in 2019) and 93 % by value ($69.5 million in 2019).

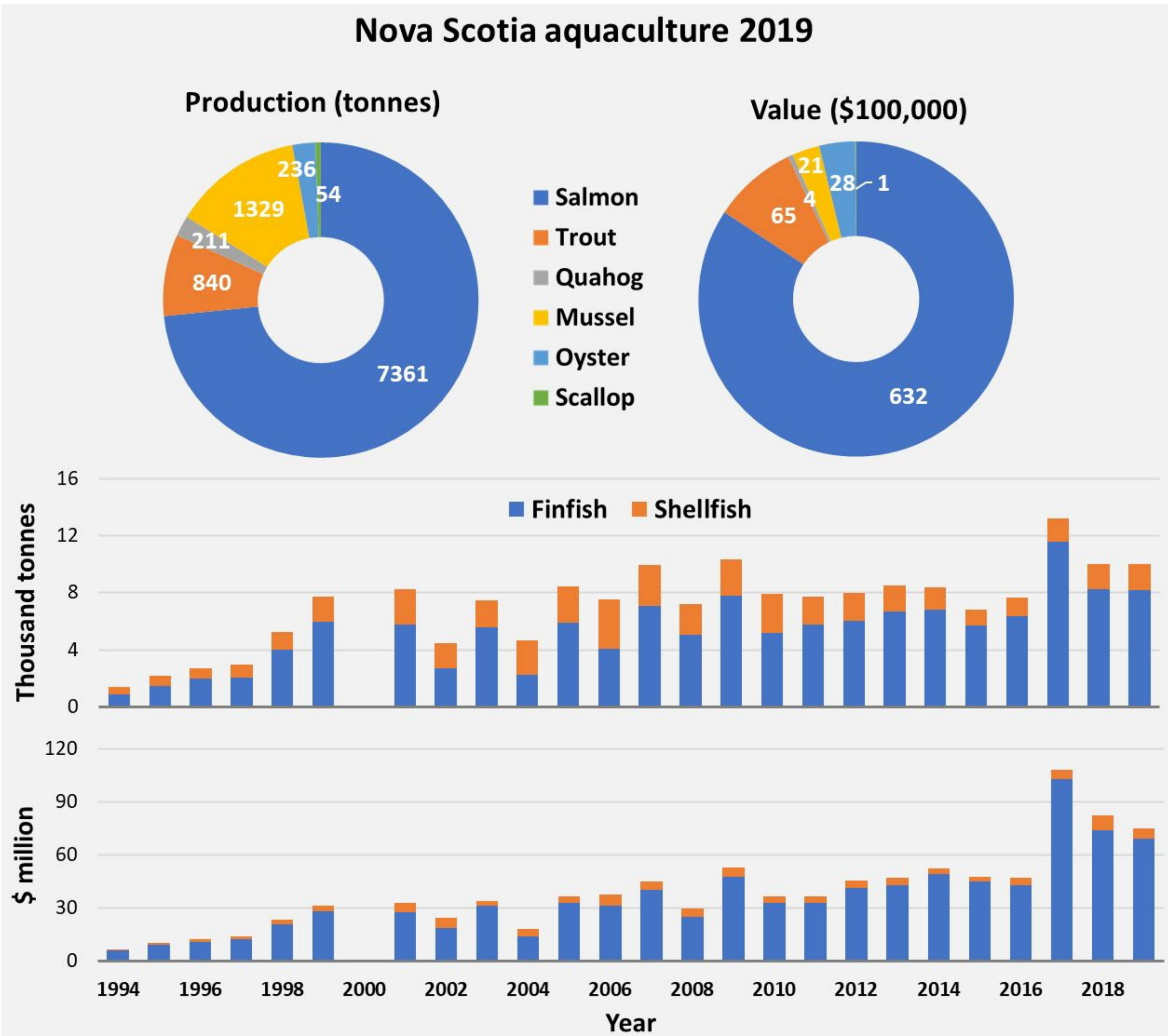

Figure 10 | Aquaculture production levels and value in Nova Scotia for 2019 divided by species (top), and over time (bottom) divided by finfish and shellfish. Salmon = Atlantic salmon, trout = rainbow and brook trout, mussel, = blue mussel, oyster = American oyster, scallop = sea scallop. Source: Nova Scotia Department of Fisheries and Aquaculture (2020c). Gaps represent years with no available data.

Although finfish aquaculture dominates production and value in Nova Scotia, there are currently many more marine aquaculture leases issued for the production of shellfish (169 leases) than finfish (35 leases) (Nova

Scotia Department of Fisheries and Aquaculture 2020a). Blue mussels (*Mytilus edulis*) make-up the majority of shellfish production in Nova Scotia, representing 13 % of all aquaculture production by weight (1,329 tonnes in 2019) and 3 % by value ($2.1 million in 2019). Production of American oyster (*Crassotrea virginica*) generates comparatively more value ($2.7 million in 2019) than blue mussel, despite production being substantially lower (236 tonnes in 2019). A small number of shellfish growers in Nova Scotia produce clams (quahog, *Arctica islandica*, and soft-shell clams, *Mya arenaria*), and scallops (bay scallop, *Argopecten irradians*, and sea scallop, *Placopecten magellanicus*). There are also initiatives underway to facilitate further growth of the shellfish aquaculture industry such as the proposed Aquaculture Development Area (ADA) in Lobster Bay. This is currently under assessment by Nova Scotia Department of Fisheries and Aquaculture (NSDFA) and the Municipality of the District of Argyle (www.aquacultureargyle.com) and will focus primarily on shellfish and marine plants. ADA's aim to attract investment from growers to establish new operations within pre-defined areas that have already been assessed, through a public process, to be socially, environmentally, and economically suitable for aquaculture development (Matthew King, NSDFA, pers. comm. 30th July 2020).

In Nova Scotia, 76 % of all issued aquaculture leases are situated in waters less than 5 m deep, of which 96 % are within 800 m from the shore. These leases all produce shellfish as finfish production generally requires greater depths (see Section 6.2.1). Consequently, there is greater potential for shellfish aquaculture to directly overlap with suitable eelgrass habitat than finfish aquaculture (Figure 11).

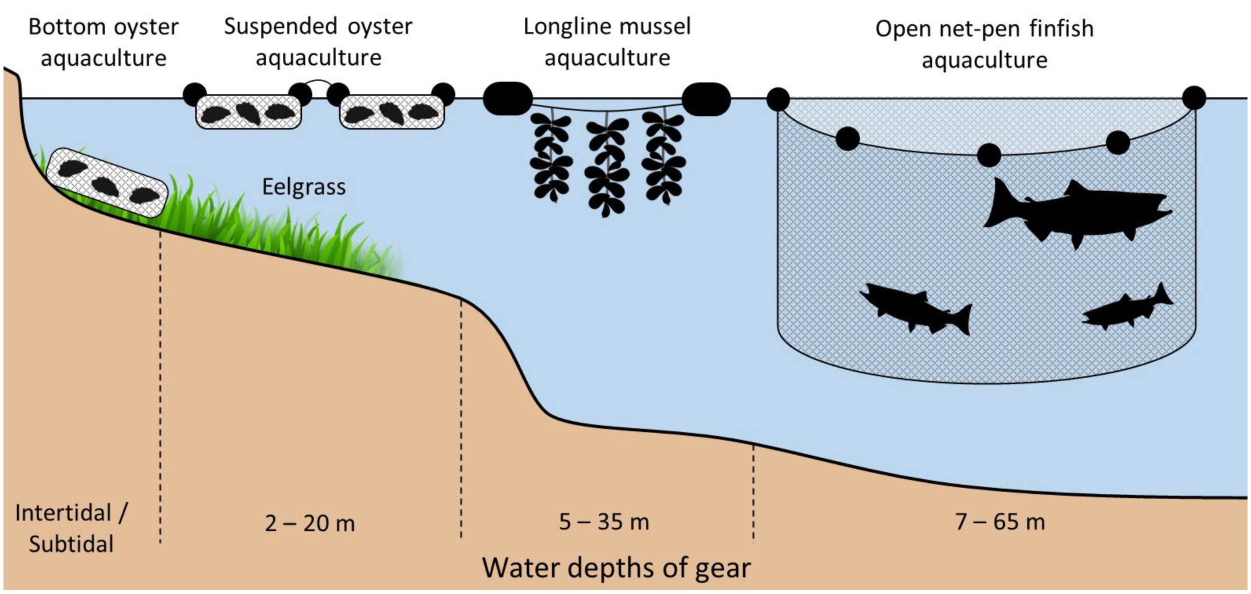

Figure 11 | Schematic diagram indicating the depth range of common aquaculture production methods in Nova Scotia. As depth increases, their chance of overlapping with eelgrass habitat diminishes. Diagram is not to scale.

6.2. Overview of production methods

6.2.1. Finfish aquaculture

In Nova Scotia, finfish farm leases are generally situated in coastal waters 100 – 1700 m from the shore in depths of 7 – 65 m (data range provided by Nova Scotia Department of Fisheries and Aquaculture - NSDFA). Farms typically comprise of 2 – 20 circular net-pens, measuring 20 – 40 m in diameter, which extend approximately 8 – 10 m downwards into the water (Nathaniel Feindel, NSDFA, pers. comm. 26th August 2020). Other site infrastructure include large moorings which anchor the pens to the seafloor, inner and outer marker buoys, and large facilities have feed barges which deliver feed pellets to the pens via a series of surface pipes and blowers (Figure 12). Salmon production is typically an 18 month cycle which begins with the stocking of hatchery-reared smolts (body mass ~110 g) in the spring (Reviewed in Chang 1998). These are then harvested as full-size adults (body mass ~6 kg) during the winter of the following year. Trout production follows a similar process and timeline.

Figure 12 | A typical finfish farm in Nova Scotia comprising of two rows of 7 pens, a feed barge, feed pipes, and inner and outer marker buoys. Source: Kevin Schyf.

6.2.2. Mussel aquaculture

Mussel farms in Nova Scotia are generally situated in coastal waters 150 – 1200 m from the shore in depths of 5 – 35 m (Nova Scotia Department of Fisheries and Aquaculture 2020a). Most mussel farms use a suspended longline system (Figure 13), where multiple longlines are suspended in the water by surface buoys (Reviewed in Scarratt 2000, Fisheries and Oceans Canada 2015, Clements and Comeau 2019). Longlines typically measure between 100 – 200 m in length and can be sunk to deeper waters to avoid winter sea ice. Production usually begins in May – June, when wild mussel seed are collected on lengths of rope, or mesh, hanging down from the longlines. The seed are then allowed to grow until late October – November until they reach around 12 – 20 mm long. Following this, the seed are harvested and placed inside polyethylene 'sleeves' or 'socks' measuring up to 2 m in length which are hung from the longlines. It then takes the mussels around 15 – 24 months to reach a marketable size.

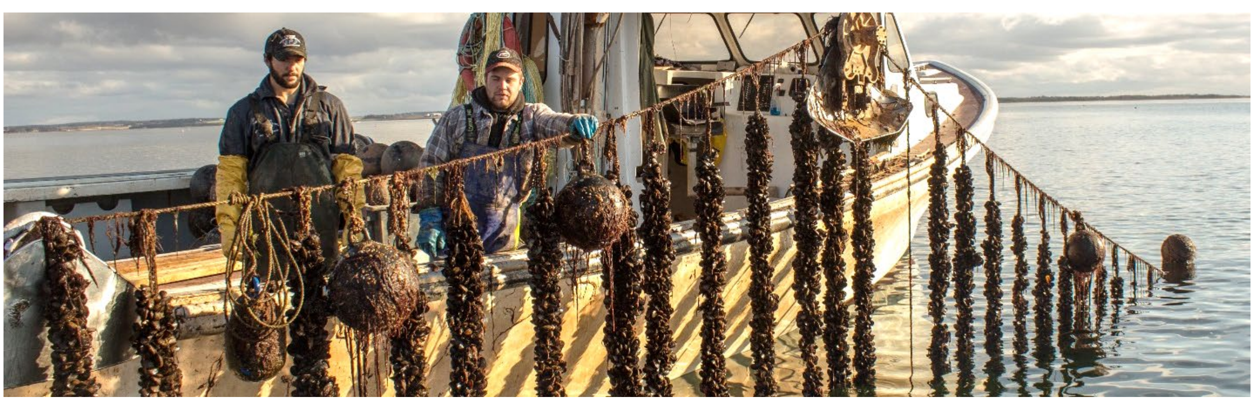

Figure 13 | A boat hauls up a series of mussel socks attached to a single longline. The longline is suspended in the water by multiple surface buoys. Source: Aaron Ramsay.

6.2.3. Oyster aquaculture

In Nova Scotia, oyster farms are generally situated in coastal waters ranging in depth from the intertidal zone to 20 m, and located up to 3 km from shore (Nova Scotia Department of Fisheries and Aquaculture 2020a). Several different production methods are used in Atlantic Canada but most growers use suspended bag or suspended cage systems. This involves growing oysters inside mesh bags or cages which are suspended at, or just below, the surface from a series of longlines. Rope culture is an alternative form of suspension oyster aquaculture and involves directly attaching oysters to lengths of rope hanging from the longlines. Like mussel farming, oyster longlines can be held afloat by surface buoys, or the bags / cages themselves may be equipped with floats (Figure 14). To avoid sea ice and storms, bags / cages can be submerged to rest on the seafloor within the lease site, or within a separate lease site dedicated to overwintering. Not all oyster growers in Nova Scotia sink their gear during the winter but are generally prepared to do so if water temperatures drop below 2°C (Scott Samson, Louisberg Seafoods, pers. comm, March 2021). Some growers in Nova Scotia use a more traditional 'on-bottom' production method where oyster bags or cages rest directly on the sediment within the shallow subtidal zone, and can be exposed during low tide (Nathaniel Feindel, NSDFA, pers. comm. 27th August 2020). In some cases, oysters are seeded directly onto the seabed without use of gear (Jeffrey Barrell, DFO, pers. comm. 29th September 2020).

Figure 14 | An oyster farm using floating cages. The cages can be rotated every few weeks to reduce biofouling and submerged to avoid winter sea ice. Source: Aaron Ramsay.

Most growers collect wild oyster seed by deploying spat collectors, or they purchase seed from other growers (Aaron Ramsay, Government of PEI, pers. comm. 31st August 2020). However, the collection of wild seed has become increasingly unreliable in Nova Scotia (Rod Beresford, Cape Breton University, pers. comm, 19th November 2020). While there are some oyster hatcheries in New Brunswick and Prince Edward Island, government regulations state that growers in the Bras d'Or lakes, Cape Breton, cannot import or export seed due to disease transmission risk (AAC 2012). Consequently, consistent and reliable access to seed is one of the biggest concerns for oyster growers in Nova Scotia (Mayer 2019). The grow-out period takes approximately 3 – 4 years before the oysters reach a marketable size (reviewed in Bastien-Daigle et al. 2007, Skinner et al. 2013).

6.2.4. Clam aquaculture

In Nova Scotia, clam aquaculture is conducted within the intertidal zone without any on-site infrastructure (Doug Bertram, pers. comm. 30th July 2020). Production begins by planting hatchery-reared seed into intertidal mud flat areas, known as 'seed beds'. The clams reach marketable size after approximately 20 months and are then harvested by hand using a rake, or 'hack' (Figure 15). Ideally, harvesting occurs at a rate that allows the seed bed to self-recruit and regenerate, without the need for more hatchery-reared seed. Consequently, clam aquaculture in Nova Scotia can be considered a type of 'enhanced fishery'.

Figure 15 | Two workers harvesting clams by hand from seed beds located on intertidal mud flats in Nova Scotia. Source: Doug Bertram.

6.2.5. Scallop aquaculture

Scallop farms in Nova Scotia are generally situated in coastal waters ranging between 5 – 35 m in depth, at a distance of 100 – 1500 m from shore (Nova Scotia Department of Fisheries and Aquaculture 2020a). Most farms produce sea scallops, however, some farms in the Gulf of St Lawrence produce bay scallops where water temperatures are suitably warmer. Growers of sea scallops generally purchase their seed from collectors based in Cape Breton (Duncan Bates, pers. comm. 30th July 2020). The seed are then suspended from longlines inside pearl or lantern nets, or via an 'ear hanging' system, where scallops are attached directly to the longlines (Figure 16). Due to strong tidal currents, growers in the Bay of Fundy use a different system where scallops are held in cages attached to frames anchored to the seafloor. Scallop seed take around two years to reach a marketable size.

Figure 16 | A Nova Scotia scallop farm utilizing a combination of ear hanging (left image) and lantern nets (right image). Source: Duncan Bates.

7. Aquaculture and the environment

7.1. The effects of finfish aquaculture on water and sediment biochemistry

The finfish aquaculture industry in North America and Europe primarily uses open net-pens situated in coastal waters. As open net-pens are designed to maximise water exchange, any resulting nutrient wastes are released into the surrounding water (Lawson 1995). These wastes can de divided into two categories; 'particulate' and 'dissolved'.

Particulate wastes derive from faeces and uneaten feed, and represent most of the carbon released from finfish farms (Islam 2005, Wang et al. 2012, Reid et al. 2013). Particulate wastes tend to settle quickly onto the seafloor and rarely disperse more than a few hundred metres (Brager et al. 2015, Price et al. 2015, Bannister et al. 2016, Filgueira et al. 2017). Consequently, they can accumulate under the pens and form a nutrient-enriched layer of organic matter overlying the sediment. Similar to the effects of eutrophication and nutrient enrichment (see Section 5.4), this organic matter can boost bacterial decomposition and lead to oxygen depletion and the build-up of sulphides within the sediment (Holmer et al. 2007, Pusceddu et al. 2007, Hargrave 2010, Price et al. 2015, Hamoutene et al. 2018). However, the quantity of particulate wastes produced by fish farms has been significantly reduced over the last three decades due to the development of more efficient feeds and feeding systems (Islam 2005, Sørensen 2012, Sprague et al. 2016).

Dissolved wastes are excreted by fish directly into the water column and represent the majority of nitrogen released from finfish farms (Norði et al. 2011, Wang et al. 2012). Up to 90 % of all the nitrogen excreted by marine finfish occurs as ammonia (NH_3), which quickly converts to ammonium (NH_4^+) at the pH of seawater (reviewed in Leung et al. 1999). Consequently, several studies have reported elevated NH_4^+ concentrations close to fish farms (Navarro et al. 2008, Sanderson et al. 2008, Jansen et al. 2018). Similar to eutrophication and nutrient enrichment (see Section 5.4), these elevated nitrogen concentrations can stimulate the growth of phytoplankton and macroalgae, thereby reducing oxygen levels and light availability (Cloern 2001, Robinson et al. 2005, Holmer et al. 2008b). However, a comprehensive review by Price et al. (2015) showed that most studies have found no direct evidence of fish farms increasing dissolved nitrogen concentrations of surrounding waters. This is partly because dissolved nitrogenous wastes can be quickly diluted and dispersed by tides and currents, rapidly assimilated by marine organisms (e.g. bacteria, phytoplankton, macroalgae and seagrass), and lost to the atmosphere through volatilization (Dalsgaard and Krause-Jensen 2006, Dailer et al. 2010). Hence, any localized increase in dissolved nitrogen is likely to be small, short-lived and difficult to detect (reviewed in Howarth et al. 2019). As a result, only finfish farms located in highly sheltered areas with low water exchange (i.e. low water turnover / high retention time) have been linked to eutrophication. For example, Pitta et al. (2005) investigated several fish farms in the Baltic Sea and only those located within small, shallow coastal bays (< 0.7 km^2) with low water turnover times (2 – 6 days) were found to increase phytoplankton and macroalgae growth.

7.2. Finfish aquaculture and seagrass interactions

7.2.1. Evidence from the Mediterranean Sea

Nearly all investigations into the impact of finfish aquaculture on seagrasses have been conducted in the Mediterranean Sea, and have examined the response of two species of Neptune grass (*Posidonia oceanica*, and to a lesser extent, *Cymodocea nodosa*) to finfish farms stocked with gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*). In general, these studies have reported decreasing seagrass cover with increasing proximity to finfish farms for distances up to 300 m, and the absence of seagrass directly under them (Table 2). These trends have been linked to increases in water and sediment nutrient concentrations, sediment organic matter, sedimentation, epiphyte loads, and increased grazing pressure from sea urchins (*Paracentrotus lividus* and *Arbacia lixula*) and other herbivores (reviewed in Holmer et al. 2008a, Cullain et al. 2018).

Table 2 | Overview of published responses of Neptune grass (*P. oceanica*, and *C. nodosa*) in close proximity to open net-pen finfish farms in the Mediterranean Sea.

Category	Parameter	Response	References
Seagrass physiology	Tissue carbohydrates	Decrease	Delgado et al. (1997), Ruiz et al. (2001)
	Photosynthesis	Decrease	Delgado et al. (1997), Cancemi et al. (2003)
Meadow structure	Above and below ground biomass	Decrease	Delgado et al. (1999), Apostolaki et al. (2009)
	Percentage cover	Decrease	Delgado et al. (1997), Ruiz et al. (2001), Holmer et al. (2008a)
	Shoot density	Decrease	Delgado et al. (1999), Pergent et al. (1999), Ruiz et al. (2001), Apostolaki et al. (2009), Rountos et al. (2012)
	Shoot mortality	Increase	Diaz-Almela et al. (2008), Holmer et al. (2008a)
Morphology	Leaf growth	Decrease	Ruiz et al. (2001)
	Leaf area / shoot size	Decrease	Delgado et al. (1999), Holmer et al. (2008a), Apostolaki et al. (2009), Rountos et al. (2012)
	Rhizome growth	Decrease	Delgado et al. (1999), Marbà et al. (2006)
Associated community	Epiphyte load	Increase	Delgado et al. (1997), Delgado et al. (1999), Pergent et al. (1999), Cancemi et al. (2003)
	Grazing pressure	Increase	Delgado et al. (1997), Delgado et al. (1999), Ruiz et al. (2001), Holmer et al. (2008a), Ruiz Fernandez et al. (2009)

Mediterranean finfish farms are quite different to those in Atlantic Canada because Mediterranean farms are generally situated in low nutrient ('oligotrophic') waters, in very shallow depths (usually 5 – 10 m), close to shore (within 200 – 500 m) in highly sheltered areas. In addition, Neptune grass (specifically *P. oceanica*) has a depth limit of around 40 m (Mayot et al. 2006, Ivana et al. 2020), which is much deeper than the 12 m maximum depth reported for eelgrass (Moore and Short 2006). Consequently, there may be less potential for finfish aquaculture in Atlantic Canada to overlap with / impact eelgrass as ambient water nutrient levels are higher (Powley and Krom 2017) and because sites tend to be located in deeper waters located further from the shore (see Section 6.2.1). It is also highly likely that finfish aquaculture sites in Atlantic Canada are more exposed to waves, wind, tides, and currents which should encourage greater dispersal of dissolved and particulate wastes (reviewed in Howarth et al. 2019).

7.2.2. Evidence from Nova Scotia

To date, only one field study has investigated finfish aquaculture and seagrass interactions outside of the Mediterranean. This was conducted by Cullain et al. (2018) at a finfish farm in Port Mouton Bay, located on the south shore of Nova Scotia, at a depth of 12 m. Eelgrass patches in depths of 1.7 – 2.9 m were surveyed at 300 m, 700 m, and 3 km from the fish farm, and compared to eelgrass beds in the neighbouring bay of Port Joli, and seven other reference areas located on the south and eastern shore of Nova Scotia. Results indicated that eelgrass cover was statistically lower in Port Mouton Bay than the reference areas, and that eelgrass cover exhibited a general declining trend with increasing proximity to the fish farm. Shoot density, and above and below ground biomass also exhibited similar trends but were not statistically significant. Likewise, there was no difference in canopy height or tissue nitrogen content between eelgrass patches near the farm compared to reference areas. All other variables exhibited inconsistent trends. For example, epiphyte cover was substantially higher in eelgrass patches located 700 m away from the farm but was almost non-existent 300 m and 3 km away. A modelling study also suggested a link may exist between anecdotal reports of eelgrass deterioration within the bay and nitrogen effluents emanating from the finfish farm (Cullain et al. 2018). However, a subsequent modelling study concluded that dissolved nitrogen concentrations within Port Mouton Bay during the operation of the fish farm were well below the expected toxicity threshold for eelgrass (Filgueira et al. 2021).

Overall, finfish aquaculture and seagrass interactions are less clear in Port Mouton Bay than studies in the Mediterranean (see Section 7.2.1). Nevertheless, a single field study is insufficient to reach definitive conclusions on finfish aquaculture / seagrass interactions in temperate ecosystems. Thus, further investigation is warranted.

7.3. The effects of shellfish aquaculture on water and sediment biochemistry

Mussels, oysters, scallops, clams and other 'bivalves' feed by pumping in water and filtering out food particles comprising of bacteria, phyto- and zooplankton, detritus, and other organic matter (Newell 2004). After ingestion, particles are sorted, digested, and excreted in the faeces, or ejected as undigested 'pseudofaeces'. Both sink towards the seafloor following release and are collectively referred to as 'biodeposits' (Shumway et al. 1985, Beninger et al. 1999). As biodeposits transfer nutrients from the water column to the seabed, they can increase the nutrient and organic content of sediments underlying shellfish farms (Crawford et al. 2003, Dumbauld et al. 2009). This can lead to enhanced bacterial activity, and where oxygen depletion occurs, an increase in sulphides (Nizzoli et al. 2006, Hargrave et al. 2008, Vinther and Holmer 2008, Richard et al. 2013). Conversely, by removing organic particles from the water column, high bivalve densities can reduce suspended nutrient levels and turbidity, increasing the amount of light reaching the seafloor (Newell and Koch 2004, Ferreira and Bricker 2019, Petersen et al. 2019). Bivalves also excrete nitrogenous wastes (mostly NH_4^+) directly into the water column which can influence coastal nitrogen cycling (Pietros and Rice 2003, Cranford et al. 2007, Ferreira and Bricker 2019).

7.4. Shellfish aquaculture and seagrass interactions

7.4.1. Positive effects

It has been suggested that bivalve aquaculture may have some positive effects on seagrass. This is because bivalves can reduce turbidity and suspended nutrient loads, which can provide more light to seagrasses (Newell and Koch 2004, Ferreira and Bricker 2019, Petersen et al. 2019). Also, their biodeposits can increase sediment nitrogen and phosphorus concentrations, which can provide more nutrients for seagrass growth (Peterson and Heck 2001, Newell and Koch 2004, Dumbauld et al. 2009, Skinner et al. 2014). For example, a study in Baja California, Mexico, found evidence that suspended oyster farms elevated water and sediment NH_4^+ concentrations, which correlated with greater eelgrass shoot size, leaf growth, and photosynthesis (Sandoval-Gil et al. 2016). Similarly, the establishment of a suspended oyster farm in New Zealand correlated with an increase in seagrass cover beneath and adjacent to the farm (Bulmer et al. 2012). Evidence from Japan suggests that oyster farms can also reduce eelgrass epiphyte loads by feeding on suspended benthic diatoms that would otherwise settle upon the eelgrass (Smith et al. 2018). Likewise, field experiments in Florida, USA, found high mussel densities reduced seagrass epiphyte loads and increased sediment nutrient concentrations, resulting in an increase in eelgrass leaf size and growth rates (Peterson and Heck 2001).

7.4.2. Neutral and negative effects

Despite the potential for shellfish aquaculture to benefit seagrass (see Section 7.4.1), most studies suggest shellfish aquaculture has a neutral or negative effect on seagrass. Skinner et al. (2013) surveyed 15 suspended oyster bag farms in Eastern New Brunswick and observed eelgrass meadows with 5 % lower above and below ground biomass within lease sites compared to reference sites 300 m away, and that these differences reached as high as 79 % in some areas. These negative effects were largely limited to a 25 m radius from lease boundaries which quickly diminished with increasing distance form the farms. They also observed that eelgrass growing within lease site boundaries displayed a 38 % reduction in photosynthetic efficiency and capacity, suggesting shading from aquaculture infrastructure was the main factor responsible for these negative trends. Subsequent field experiments supported this notion as shading from oyster cultures reduced eelgrass shoot density, above and below ground biomass, canopy height, leaf size and photosynthetic capacity (Skinner et al. 2014). These negative responses were detected within 67 days after exposure to 26 % subsurface irradiance and exhibited no substantial recovery 253 days after shading treatments were removed.

On a larger scale, a recent meta-analysis examined 125 studies on the effects of shellfish aquaculture on eelgrass (Ferriss et al. 2019). Generally, all methods had negative effects on eelgrass density and biomass, however, the extent of these impacts were highly variable and depended on the production and harvest methods being used. For instance, longline methods negatively impacted eelgrass density, whereas suspended bag aquaculture had a neutral effect. This could be because suspended bag methods allow more light to penetrate to the seafloor. Oyster culturists in new Brunswick, for example, intentionally leave some slack in their lines to allow the bags to move with the tides, reducing physical strain on the gear (Transport Canada 2007, Skinner et al. 2013). This movement would also prevent any areas of the seabed from becoming permanently shaded, potentially permitting the growth of eelgrass. In support of this, dense beds of seagrass have been observed to grow under suspended oyster bags / baskets in Australia (Crawford et al. 2003) and studies have shown that suspended bag aquaculture can result in 68 % less shading than other 'off-bottom' production methods (Madigan et al. 2000).

The meta-analysis by Ferriss et al. (2019) also showed that, for production methods which required workers to harvest shellfish from the sediment (e.g. clam aquaculture and some oyster production methods), mechanical harvesting methods (e.g. dredging, dragging and sediment liquefaction) had the largest initial impact on eelgrass meadows and required the longest time for recovery. Conversely, manual harvest methods (e.g. by hand, or hand tools like rakes and hoes) had less impact on eelgrass, presumably because they can be more spatially targeted, resulting in less disruption to eelgrass roots and rhizomes, and faster recovery times (Cabaço et al. 2005, Wootton and Keough 2016).

8. Aquaculture and eelgrass management in Atlantic Canada

8.1. Regulation in Nova Scotia

Aquaculture is jointly managed by federal and provincial governments, the nature of which varies between provinces (Fisheries and Oceans Canada 2020a). At the federal level, DFO is the primary department responsible for regulating aquaculture through the *Aquaculture Activities Regulations* (SOR/2015-177) which were created under the *Fisheries Act* (R.S.C. 1985). On a provincial level, the *Fisheries and Coastal Resources Act* (S.N.S. 1996) is the primary law governing aquaculture in Nova Scotia, along with the *Aquaculture Licensing and Leasing Regulations* (N.S. Reg. 347/2015) and *Aquaculture Management Regulations* (N.S. Reg. 348/2015). NSDFA are the lead regulators of aquaculture in Nova Scotia and Nova Scotia Environment are responsible for the compliance and enforcement of the *Fisheries and Coastal Resources Act* (Nova Scotia Environment 2020). NSDFA are responsible for issuing aquaculture licenses and leases, performing site visits and other administrative checks, and specifying management measures regarding fish health. Both NSDFA and DFO share the responsibility for environmental management and monitoring (Nova Scotia Department of Fisheries and Aquaculture 2019a).

All aquaculture sites in Canada require a valid lease and licence. The lease entitles the owner or operator to install and use aquaculture gear in a specified area. Whereas the licence allows the owner or operator to stock the facility, subject to conditions specified within the licence. In Nova Scotia, aquaculture license and lease applications undergo either an 'administrative' or 'adjudicative' decision process (reviewed in Nova Scotia Department of Fisheries and Aquaculture 2020d). The administrative decision process is overseen by NSDFA, and covers applications for land-based operations, as well as marine operations regarding experimental licenses and leases, renewals of existing licenses and leases, and amendments to existing licenses and leases that do not result in the expansion of the site or the addition of finfish to a site that is currently not approved for finfish. In contrast, the adjudicative decision process is overseen by the Nova Scotia Aquaculture Review Board (https://arb.novascotia.ca/) and covers applications for new marine licenses and leases, as well as amendments to existing licenses and leases that expand site boundaries or add finfish to the species being cultured.

All aquaculture applications are reviewed by NSDFA and network partners. Network partners consist of a range of provincial and federal departments that have regulatory jurisdiction over certain aspects of aquaculture. This may involve several groups within DFO including the Fish and Fish Habitat Protection Program, Aquaculture Management, the Marine Planning and Conservation program and DFO Science. DFO's fisheries departments may also be involved as mussel and oyster seed collection outside aquaculture leases is considered a fisheries-related activity. Other federal departments like CWS, Transport Canada (TC) and the Canadian Food Inspection Agency (CFIA) may also be involved in the process (Jeffrey Barrell, DFO, pers. comm. 21st July 2020). Together, NSDFA and network partners evaluate the potential environmental impacts of aquaculture proposals based on published scientific research, and physical and ecological data collected during baseline sampling (Nova Scotia Department of Fisheries and Aquaculture 2019b).

Proposed / existing aquaculture operations must undergo baseline / repeated (finfish leases only) environmental monitoring as specified within the federal *Aquaculture Activities Regulations* (Department of Fisheries and Oceans 2018) and provincial Environmental Monitoring Program (Nova Scotia Department of Fisheries and Aquaculture 2020e). These aim to minimize impacts on fish and fish habitat and to allow regulators to impose mitigative measures if an aquaculture operation was deemed to be significantly impacting the marine environment (Nova Scotia Department of Fisheries and Aquaculture 2020b). Exact sampling strategies are determined by a number of factors including sediment composition (i.e. soft or hard bottom), the scale of the operation, and the species being cultured (i.e. shellfish or finfish). For baseline sampling, a number of video transects across the seabed have to be conducted within the proposed lease site, and videos may be required at each corner of the site as well. The raw video footage (and any data reports if required) are then submitted to NSDFA and DFO for review. As the protection of ecosystems and fish habitat falls under the mandate of DFO (Fisheries and Oceans Canada 2021), DFO are responsible for determining if the aquaculture operation poses a risk to eelgrass and other fish habitat, and whether additional mitigation or avoidance measures are needed (Edward Parker, DFO, pers. comm. 4th August 2020). For instance, DFO may: require the operator to place anchors away from sensitive habitats; specify a minimum distance between rows of gear; and / or impose a cap to the maximum area of the lease site they can occupy with gear (Danielle St. Louis, NSDFA, pers. Comm, March 2021).

These evaluations and recommendations are then submitted to the Nova Scotia Aquaculture Review Board (if undergoing an adjudicative application process) who hold an independent tribunal, in which applicants and stakeholders (e.g. members of the public and local industries) present their evidence in support of, or opposition, to the application. The Board then decides whether the application is approved based on appropriate support data presented during the tribunal, and from the recommendations received from NSDFA, DFO and other network partners.

8.2. Aquaculture as a prescribed activity

As discussed earlier (see Section 4.5), section 35 of the *Fisheries Act* legally prohibits a HADD to eelgrass and other fish habitats. However, exceptions are granted to works, undertakings or activities that will result in a HADD if they are 'prescribed' or belong to a 'prescribed class', or if permission is granted by a federal authority (Fisheries and Oceans Canada 2020f). As the installation, operation, maintenance, and removal of aquaculture facilities are prescribed in the *Aquaculture Activities Regulations*, they are excepted providing the conditions in the regulations are met. One of the main conditions is that "reasonable measures" must be taken to avoid and minimize impact to fish habitat (Edward Parker, DFO, pers. comm. 4th August 2020).

8.3. The Bay Management Framework (BMF) in New Brunswick

It is difficult to empirically test whether aquaculture operations directly impact eelgrass beds. Not only are eelgrass beds highly dynamic (see Section 2), provincial and federal regulators typically have access to very little data on eelgrass (such as their location, density, and health) and do not have the resources to perform detailed surveys on a large scale. To overcome these issues, federal and provincial agencies in Eastern New Brunswick have implemented a comprehensive Bay Management Framework (BMF) for suspended oyster aquaculture. The BMF established a broad range of site selection criteria and operating guidelines for suspended oyster aquaculture, which help ensure oyster farms have minimal impact on eelgrass and other species and habitats, while creating no additional data collection requirements on growers and regulators. Provided growers follow these guidelines, regulators assume suspension oyster aquaculture has a negligible impact on eelgrass in Eastern New Brunswick. As the constraints imposed by the BMF are considered more than sufficient to prevent aquaculture from impacting eelgrass, aquaculture does not trigger a HADD, and no environmental assessments are required.

A key reason for the creation of the BMF was to reduce administration loads on growers, as well as federal and provincial agencies. Prior to 2012, proposals for new aquaculture operations and amendments had to undergo an Environmental Impact Assessment (EIA) under the *Canadian Environmental Assessment Act* (S.C. 1992). As the suspended oyster aquaculture industry was undergoing rapid expansion during this time, DFO, TC, and other federal agencies were receiving hundreds of EIAs each year for small (~ 5 ha) suspended oyster farms. Not only did this impose large time and financial costs on growers and federal agencies, the proposed oyster farms were all similar in design, meaning similar environmental effects were expected. Consequently, the EIAs were largely identical and comments from federal agency reviewers were repetitive. Furthermore, the site-by-site application process did not consider cumulative impacts and potential conflicts between multiple coastal users. To address these issues, TC and DFO compiled a 'replacement class screening report' that streamlined the EIA process for suspended oyster farms in Eastern New Brunswick (Transport Canada 2007). The *Canadian Environmental Assessment Act* (S.C. 2012) was later revised in 2012 and no longer required aquaculture projects to undergo an EIA. Therefore, the replacement class screening report was also revised based on lessons learned during the intervening years, and superseded with a Comprehensive Environmental Effects Determination (CEED) report (Transport Canada 2013).

Both reports established a BMF for suspended oyster aquaculture farms on leases managed by the New Brunswick Department of Agriculture, Aquaculture and Fisheries (DAAF). A key component of the BMF was the identification and mapping of all areas in Eastern New Brunswick were deemed suitable for suspended oyster aquaculture. Then, based on existing data and knowledge, a series of buffer zones were created including: a 100 m buffer from the low water mark; 300 m buffers around any conservation areas, species of special concern, migratory birds and fish and their associated habitats; and navigation corridors every 400 m to ensure water users could navigate between leases and still gain access to the shore. Zones were then defined indicating where aquaculture leases already existed, and where new shellfish leases would be best located to protect the environment and avoid conflict with other coastal users. These maps were developed in partnership with a wide range of federal and provincial agencies, and in consultation with a variety of industry, environmental, community and First Nations groups. Overall, this approach represented an early implementation of the principles of Marine Spatial Planning (MSP), which is currently being pursued by federal and provincial regulators for the management of aquaculture and other ocean-based activities across Canada (Fisheries and Oceans Canada 2018). This style of approach is also used by NSDFA and the Municipality of the District of Argyle in the Lobster Bay ADA (see Section 6.1).

The creation of the replacement class screening and CEED documents also involved an extensive consultation process with growers, regulators, researchers, public and other stakeholders. Through these consultations, and by reviewing existing research, it was concluded that shading was the primary impact of suspended oyster aquaculture on eelgrass. Nutrient enrichment of underlying sediment was considered unlikely as all leases were situated in areas with water current velocities greater than 0.2 m s^{-1}, which exceeds the level required to re-suspend and disperse biodeposits (Widdows et al. 1998, Giles and Pilditch 2004). Therefore, the CEED report established a broad range of operating conditions aimed at preventing oyster aquaculture gear from damaging eelgrass through excessive and persistent shading:

- Operators cannot harvest, or knowingly destroy, marine plants;
- To reduce damage to eelgrass and prevent dragging of gear, operators must size anchors appropriately, or install them permanently;
- Anchors should be installed in winter when the effects of turbidity on eelgrass are minimal;
- Gear must be anchored in a way that allows it to sway and move during each tidal cycle;
- Structures should be designed and installed to maximize light penetration to seabed;
- Moorings and other structures are encouraged to be placed away from eelgrass;
- Gear cannot cover more than 50 % of a lease site;
- Rows of gear must be spaced at least 3 m apart; and
- Dead oysters and their shells must be disposed of on land.

DAAF have also capped the total coverage of suspended oyster aquaculture in a single bay to 10 % to help protect eelgrass and other habitats, and to help reduce conflict with other users. Preliminary calculations suggest that the current level of aquaculture in Eastern New Brunswick is likely reducing eelgrass productivity by just 0.1 % but could reach as high as 0.3 % if the 10 % bay limit was reached. Both are considered sustainable and in-line with levels caused by natural variability (Joseph LaBelle, DAAF, pers.com, August 28th 2020).

Overall, the BMF and CEED guidelines are widely accepted by the industry and public. In fact, the oyster aquaculture industry grew by 20 % (by number of bags in the water) between 2018 – 2020, yet no disputes have been raised from the fishing industry, public and / or other stakeholders. The BMF also employs an adaptive management approach where data from any field surveys, and new scientific research, are reviewed on an annual basis to determine if any changes need to be made to the BMF. If the 10 % bay limit is ever reached, provincial and federal regulators intend to launch a new, full investigation into the measures required to ensure these sustainable aquaculture practices continue.

In summary, the BMF is a spatial management system for suspended oyster aquaculture that minimizes user conflicts, environmental impacts, and cumulative effects, without requiring any additional data collection.

9. Management recommendations

The BMF and CEED guidelines adopted in Eastern New Brunswick (see Section 8.3) have proven successful at supporting the growth of the aquaculture industry while ensuring it has minimal impacts on eelgrass. Similar to New Brunswick, there is limited data on the exact distribution and status of eelgrass beds in Nova Scotia (see Section 1.3). A similar management system could therefore offer a potential solution to aquaculture and eelgrass management in Nova Scotia. However, the CEED guidelines only address the potential impacts of suspended oyster aquaculture. Thus, this section proposes several additional measures for other forms of aquaculture in Nova Scotia, and a consultation process to help ensure the CEED guidelines are suitable for a Nova Scotian context.

9.1. Oyster, mussel, and scallop aquaculture

Shading is the primary impact of shellfish aquaculture on seagrass (see Section 7.4.2). Consequently, the CEED guidelines establish a broad range of operational guidelines that help ensure suspended oyster aquaculture does not cause excessive and permanent shading to eelgrass (see Section 8.3). Discussions could be held with oyster growers to determine if any of these CEED guidelines could be implemented in Nova Scotia. Discussions with DFO are warranted given their current recommendation for suspended shellfish aquaculture in Nova Scotia is for growers to keep their lines taut in order to reduce the risk of wildlife entanglement (Jason Naug, DFO, pers. comm, February 2021). This conflicts with the CEED guidelines in New Brunswick which require growers to maintain some slack in their lines, allowing suspended gear to move with tides and preventing any underlying eelgrass from becoming permanently shaded.

Oyster growers could also be encouraged to use suspended bag / cage methods where possible, as these generally have less impact on eelgrass than on-bottom methods (see Section 7.4). An added advantage of suspended methods is that oysters tend to be less susceptible to MSX disease (or 'Multinucleate Sphere X) compared to oysters grown using on-bottom methods (Rod Beresford, Cape Breton University, pers. comm, 19th November 2020). Nevertheless, suspended oyster gear can still come into direct contact with eelgrass and cause a physical disturbance during the winter months if / when growers sink their gear to the seabed (see Section 6.2.3). Discussions could therefore be held with industry to determine whether, in cases where oyster farms have potential to overlap with eelgrass (e.g. in depths < 12 m), growers could sink their gear in deeper areas of their lease to help avoid disturbance to eelgrass. Finally, discussions could be held with growers to determine whether any of the CEED guidelines could be applied to the suspended longline mussel and scallop industry.

Overall, any new siting and operational guidelines may only need to be imposed on shellfish leases in depths of less than 12 m, as eelgrass is highly unlikely to occur beyond this depth (see Section 1.4).

9.2. Intertidal clam aquaculture

Physical disturbance is the primary impact of intertidal shellfish aquaculture on eelgrass (see Section 7.4.2). As the intertidal clam aquaculture industry in Nova Scotia harvests and seeds clams by hand, they should be able to avoid disturbing eelgrass as the disturbance caused by these methods is highly localized. Management measures could restrict the industry from using mechanical harvesting methods given their potential to damage eelgrass and their slow recovery from such disturbances (see Section 7.4.2). As clam aquaculture is intertidal, it should be comparatively easy to determine if proposed clam aquaculture operations coincide with eelgrass, and for growers to find alternative locations if needed. A buffer approach could enable an area of protection around existing eelgrass beds, allowing eelgrass patches the opportunity to undergo seasonal and annual fluctuations in size without coming into direct contact with an operation.

9.3. Open net-pen finfish aquaculture

Nutrient enrichment and the deposition of particulate wastes are the primary impact of finfish aquaculture on eelgrass, and are usually confined to the area directly under fish pens for a radius of approximately 300 m depending on depth and current speeds (see Section 7.2). As eelgrass typically has a maximum depth of 12 m (see Section 1.4), situating finfish farms in depths greater than 12 m deep could help avoid overlap with eelgrass habitat. Locating finfish farms in areas with moderate to high current speeds would also encourage the dispersal of dissolved and particulate wastes (see Section 7.2.1), reducing their potential to elevate nutrient levels in sediments and the water column.

9.4. Consultations and adaptive management

Similar to the creation of the CEED guidelines in Eastern New Brunswick, a thorough consultation process could help ensure proposed guidelines are suitable for Nova Scotia, and agreeable to regulators, industry, and other stakeholders. A regular review process based on stakeholder and regulator feedback, and current scientific research, would help ensure ongoing appropriateness of the guidelines.

9.5. Potential differences between New Brunswick and Nova Scotia

Environmental conditions in the Gulf of St. Lawrence differ from those in Nova Scotia. For example, ice cover and scouring are greater in the Gulf, whereas wave energy is higher in Nova Scotia. There is potential for these differences to cause regional variation in how eelgrass responds to aquaculture (Melisa Wong, DFO, pers. comm, February 2021). Also, the Gulf of St. Lawrence has higher and more continuous eelgrass cover than Nova Scotia, which may make any impacts to eelgrass more ecologically significant in Nova Scotia (Jeffrey Barrell, DFO, pers. comm, March 2021). Nevertheless, the potential impacts of aquaculture on eelgrass are the same - shading by shellfish aquaculture and nutrient enrichment by finfish aquaculture. Consequently, the proposed measures described above are still applicable in protecting eelgrass from aquaculture impacts. Nevertheless, a thorough consultation process with scientists and experts would further ensure the developed guidelines are appropriate for a Nova Scotia context.

9.6. The Aquaculture Review Board

In theory, adopting the proposed guidelines described above, combined with additional research and consultations, could help ensure aquaculture in Nova Scotia has minimal impacts on eelgrass. This could enable the Nova Scotia Aquaculture Review Board (see Section 8.1) to presume that applications for new aquaculture sites and amendments will not harm eelgrass providing the industry follow these developing operational and siting guidelines.

10. Summary

Eelgrass is an 'Ecologically Significant Species' and protected under Canadian federal legislation. However, many eelgrass beds in Atlantic Canada have declined in response to a multitude of interacting stressors. As the aquaculture industry continues to grow, there is increasing potential for aquaculture to have a negative impact on eelgrass. Provincial and federal regulators typically have limited access to eelgrass data and do not have the resources to conduct detailed large-scale surveys. This can limit their capacity for evidence-based management of aquaculture and eelgrass interactions. These issues have largely been addressed in New Brunswick due to the adoption of the BMF and CEED guidelines. This management system established a broad range of operating and siting guidelines on the suspended oyster aquaculture industry that have proved effective in minimizing impacts on eelgrass, without the need for additional data collection. A similar management system could therefore offer a potential solution to aquaculture and eelgrass management in Nova Scotia. However, the CEED guidelines only address the potential impacts of suspended oyster aquaculture. Thus, this report proposes several additional measures for other gear types, as well as a consultation process, which could help reduce any potential impacts aquaculture may have on eelgrass in Nova Scotia.

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