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Gulf Region

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SPATIAL OVERLAP AND LIKELY EFFECTS OF SHELLFISH AQUACULTURE ON EELGRASS (*ZOSTERA MARINA*) IN THE SOUTHERN GULF OF ST. LAWRENCE

Context

Eelgrass is designated as an ecologically significant species in the southern Gulf of St. Lawrence (sGSL). It is suspected that eelgrass in this region is currently experiencing population change in many places. One potential driver of eelgrass declines in the sGSL is suspended shellfish aquaculture. However, interactions between cultured shellfish and eelgrass are complex and difficult to quantify and the overall risks of shellfish aquaculture to eelgrass in the region remain unclear.

This Regional Science Response Process was requested by Aquaculture Management, Fisheries and Oceans Canada (DFO) to support the ongoing delivery of DFO's role in assessing shellfish aquaculture interactions with fish and fish habitat under the Fisheries Act, as well as providing science advice to the Prince Edward Island aquaculture leasing program and Nova Scotia and New Brunswick provincial aquaculture regulators.

The request for advice is to inform our understanding of the effects of suspended shellfish aquaculture on eelgrass beds. Specifically, the spatial interactions and likely effects of shellfish aquaculture on eelgrass habitat in the sGSL, with particular focus on shading from aquaculture gear; differentiated by species, gear type, and depth.

While eelgrass can interact with shellfish aquaculture through a variety of pathways, this process focuses on the potential scope of shading on important eelgrass habitats within DFO Gulf Region. This was accomplished through a review of available scientific literature, the compilation and spatial analysis of data representing the distribution of aquaculture activities within eelgrass depth requirements, and field experiments measuring the effects of aquaculture gear on underwater light conditions.

This Science Response Report results from the Regional Peer Review of March 30, 2023 on Characterizing the effects of suspended oyster aquaculture on eelgrass in the Gulf Region.

Background

Eelgrass, Zos*tera marina* (hereafter eelgrass), is the primary seagrass species found in saline environments in the southern Gulf of St. Lawrence (sGSL) (Vandermeulen 2005). Eelgrass is a rooted marine plant with vertical leaves that is predominantly perennial; however, annual growth forms can occur under stressed conditions (Robertson and Mann 1984; note that the differences in perennial vs. annual forms are only discussed where differences in traits are critical to the context). Eelgrass coverage increases through either sexual reproduction via seeds or clonal growth and lateral extension of belowground stems known as "rhizomes". Rhizomes of an individual eelgrass plant extend through sediments in a branching pattern (Ochieng et al. 2010), with roots and leaves extending off the rhizome; horizontal rhizome extension occurs at a rate of approximately 15 cm per year (Olesen and Sand-Jensen 1994). Aboveground, eelgrass produces two structures: vegetative shoots and reproductive shoots, with the latter producing flowers and seeds through sexual reproduction (Keddy and Patriquin 1978). In the sGSL, the eelgrass canopy can reach heights of 1.3 m above the seafloor (van den Heuvel et al. 2019).

In shallow subtidal areas of the sGSL eelgrass growth is likely restricted to ice-free months, typically between April and November, with maximum biomass typically occurring in July (Clausen et al. 2014; Hitchcock et al. 2017, van den Heuvel et al. 2019). Defoliation of leaves in the winter months is common, with new leaves emerging from the rhizomes in spring (Wong et al. 2013), though there are documented cases of leaf retention throughout the winter (McRoy 1969). As such, plant characteristics (e.g., leaf length, shoot density, flowering) can vary seasonally (Clausen et al. 2014; Blok et al. 2018).

The maximum and minimum depths (i.e., intertidal) occupied by eelgrass are dependent on local environmental conditions; most notably temperature, water clarity, water currents, and ice scour (Schneider and Mann 1991; Oreska et al. 2021; Krumhansl et al. 2021; Howarth et al. 2022). For example, eelgrass has been documented at depths > 6 m in Newfoundland and Atlantic Nova Scotia and may occupy intertidal areas outside the sGSL within Atlantic Canada that do not experience winter ice scour (Robertson and Mann 1984; Warren et al. 2010; Barrell and Grant 2015; Krumhansl et al. 2021). Data describing the depth distribution of eelgrass habitat in aquaculture bays of the sGSL will be presented below.

Where present, extensive eelgrass meadows in the sGSL provide many ecosystem services. Principally eelgrass forms critical three-dimensional habitat for a multitude of species in this region (Schneider and Mann 1991; DFO 2009; Coffin et al. 2018). Many species of small-bodied fish, including juvenile stages of species of commercial, recreational, and aboriginal interest (Joseph et al. 2006; Joseph et al. 2013), seek refuge in eelgrass beds in the sGSL. Indeed, the Mi'kmaq of Atlantic Canada have long associated Qata’skwl (eelgrass) as places to find fish (CEPI 2006). Eelgrass also provides several valuable ecosystem services, including primary production, carbon sequestration, water filtration, attenuation of wave energy, and sediment stabilization (Barbier et al. 2011; Hansen and Reidenbach 2013; Orth et al. 2020). Due to this role as an “ecosystem engineer”, eelgrass was designated by DFO as an ecologically significant species (ESS) in the sGSL (DFO 2009).

Eelgrass habitat is very dynamic, forming habitat mosaic patterns ranging from highly fragmented to continuous meadows spanning multiple spatial scales (Figure 1). The eelgrass landscape is structured by several spatially and temporally variable processes and can vary considerably through time in response to changing environmental conditions (Robertson and Mann 1984; Barrell and Grant 2015; van den Heuvel et al. 2019). Eelgrass requires suitable conditions for establishment and persistence. As a rooted plant, it requires soft substrate (i.e., sand or mud) with low levels of organic matter (Hargrave et al. 2008; Coffin et al. 2018; Oreska et al. 2021). In addition, sufficient availability of light and nutrients for photosynthesis are crucial for eelgrass (Ochieng et al. 2010; Sandoval-Gil et al. 2016). Several other interacting factors can affect the health and distribution of eelgrass, including water temperature, hydrodynamic regimes, storm frequency and intensity, winter ice dynamics, grazing, invasive species, and direct anthropogenic disturbance (DFO 2009, 2012; Murphy et al. 2021; Wong and Dowd 2021).

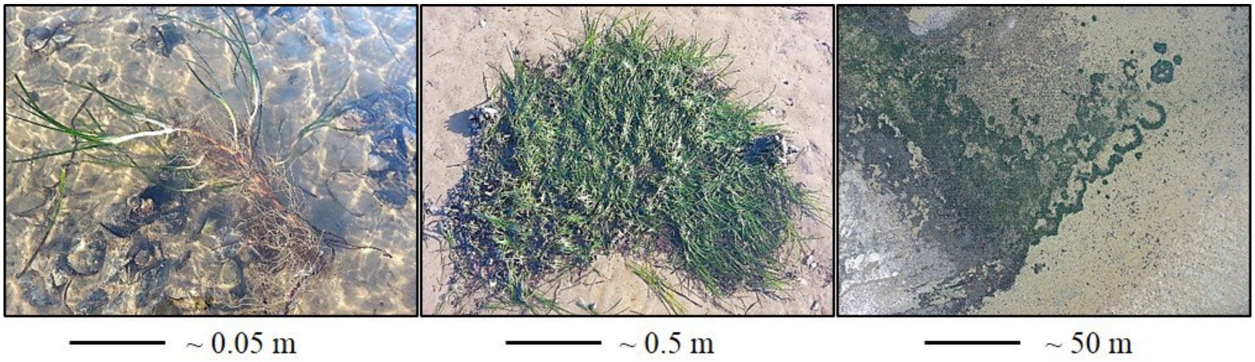

Figure 1. Hierarchy of spatial scales represented in an eelgrass landscape: (left) individual plant with leaf and rhizome structures, (center) a collection of plants forming a patch, and (right) landscape-scale mosaic of patches intermixed with a blue mussel reef. All photos taken by J. Barrell at Eastern Passage, Nova Scotia, Canada. Figure reproduced from Barrell (2014).

Eelgrass characteristics can respond to localized parameters, changing environmental conditions and stress from cumulative effects (e.g., temperature, light, nutrients, depth, current velocity, etc.) in a variety of ways (Skinner et al. 2013; Sandoval-Gil et al. 2016; Uhrin and Turner 2018). For example, light can affect physiological parameters of eelgrass in the northern Gulf of St. Lawrence (Léger-Daigle et al. 2022). Indeed, light is a primary consideration for the length of eelgrass leaves in the sGSL, with leaf length increasing relative to decreasing light levels (Schmidt et al. 2012; van den Heuvel et al. 2019). The increased energy allocation for leaf growth in low light reduces biomass within rhizomes and associated carbohydrate reserves needed for overwinter survival (Burke et al. 1996; Ochieng et al. 2010; Hasler-Sheetal et al. 2016). Moreover, the decrease in root mass under low light coupled with high sediment organic matter further reduces anchoring from long leaves relative to smaller below ground structures (Wicks et al. 2009). Such changes in morphology and biomass allocation can influence landscape patterns of eelgrass density, which relate to wave energy levels (Uhrin and Turner 2018). Genetic origins can also influence plant morphology, as densities and biomass of Atlantic eelgrass populations (distinct from Pacific populations) are a legacy of Pleistocene isolation events (Duffy et al. 2022). Furthermore, eelgrass has the potential to at least partially acclimate to localized light conditions (Léger-Daigle et al. 2022). This combination of morphology, wave energy, sediment structure, and genetic origin culminate to drive spatially-variable landscape mosaics of eelgrass (Borum et al. 2014; Barrell and Grant 2015; Duffy et al. 2022).

Eelgrass is widely distributed throughout the sGSL in areas with suitable environmental conditions (Schneider and Mann 1991; Skinner et al. 2013; van den Heuvel et al. 2019; DFO unpublished data). The historical spatial coverage of eelgrass in this region is difficult to determine (Karmakar et al. 2019; van den Heuvel et al. 2019). Wasting disease caused by the slime mold *Labyrinthula* spp. drove severe population declines of sGSL eelgrass in the 1930s, with limited recovery until the 1950s (Cottam and Munro 1954). Drastic contemporary declines in eelgrass coverage have also been reported in the sGSL, in some cases documenting bay-scale loss of up to 95% (Garbary et al. 2014; van den Heuvel et al. 2019; Murphy et al. 2021). Preliminary satellite imagery analysis corroborates recent reports of coverage declines (DFO unpublished data). Eelgrass declines in the sGSL have been linked to a multitude of factors including invasive species, human alterations to drainage basins, eutrophication, and coastal landscape alteration (Murphy et al. 2019; Skinner et al. 2013; Garbary et al. 2014; van den Heuvel et al. 2019). High summer temperatures in the sGSL may be a critical factor, as eelgrass is known to experience physiological stress above 23 °C and increased mortality above 25 °C (Nejrup & Pedersen 2008), which can occur particularly in shallow sGSL bays and estuaries (Sonier et al. 2011; Coffin et al. 2018). Stress related to eutrophication has also been identified as a critical factor in the sGSL and beyond (Lefcheck et al. 2018; van den Heuvel et al. 2019), and eelgrass can be further affected by a wide variety of nuanced and localized environmental conditions (e.g., hydrodynamics, salinity, porewater chemistry, sediment type, etc.; Nejrup & Pedersen 2008; Borum et al. 2014; Krumhansl et al. 2021; Oreska et al. 2021).

Another potential factor affecting the distribution of eelgrass in the sGSL is suspended shellfish aquaculture. Shellfish aquaculture can have negative, neutral, or positive effects on eelgrass health (Ferriss et al. 2019; Howarth et al. 2022). Shading from suspended aquaculture leases is considered the dominant driver negatively affecting eelgrass health within and near suspended bivalve leases (McKindsey et al. 2011; Skinner et al. 2014). This shading may result in eelgrass mortality within aquaculture lease footprints (McKindsey et al. 2011; Skinner et al. 2014; Ferriss et al. 2019); however, local environmental conditions, the type of shellfish aquaculture, and the spatial footprint of aquaculture activities can all influence the scale of eelgrass impact (Skinner et al. 2013; Ferriss et al. 2019). Introduced species associated with bivalve aquaculture can further shade adjacent eelgrass leaves (McKindsey et al. 2011; Carman et al. 2019). Organic matter deposition from shellfish aquaculture can also increase sulfide toxicity and affect eelgrass metabolism (Hasler-Sheetal et al. 2016), although organic waste from oysters may not build up in all eelgrass beds (Skinner et al. 2013, 2014; Comeau et al. 2014). Conversely, bivalves can increase light penetration by enhancing water clarity through filtration and can provide benefits to seagrass in some phytoplankton-dominated systems (Newell and Koch 2004; Ibarra et al. 2012); however, it is important to note this has not been explicitly demonstrated for eelgrass in the sGSL. When light availability is high, bivalves can also provide nutrients that can further stimulate eelgrass growth (Castorani et al. 2015; Sandoval-Gil et al. 2016). Consequently, the interactions between cultured sGSL bivalve species and eelgrass are complex and difficult to quantify.

While previous shading experiments have documented potential negative effects on eelgrass traits due to shading in the sGSL (Skinner et al. 2013, 2014), these experiments were conducted in the context of now largely outdated gear types and in very shallow water (0.3–0.6 m). Aquaculture gear types and culture practices have changed in recent years, and culture methods are continually shifting to deeper water. Furthermore, while experiments measuring potential effects at the farm scale exist (e.g., Skinner et al. 2013, 2014), an updated and broader spatial understanding of aquaculture impacts on eelgrass at the regional scale across the sGSL is lacking. As such, the goal of this document is to *“examine the spatial interactions and likely effects of shellfish aquaculture and eelgrass habitat in the southern Gulf of St. Lawrence, with particular focus on shading from aquaculture gear; differentiated by species, gear type, and depth”* (see Terms of Reference).

To achieve this, we reviewed the literature to synthesize the likely effects of shellfish aquaculture on eelgrass in the sGSL. We conducted experiments measuring light beneath oyster cages (the most common oyster culture gear type in the region; see section titled *Spatial interactions between shellfish aquaculture and eelgrass* below) at an oyster lease in Cocagne Bay, New Brunswick (NB) to assess farm-scale effects of oyster aquaculture on light levels and light attenuation. Finally, we compiled detailed data representing shellfish aquaculture activities in the sGSL according to species (blue mussels, *Mytilus edulis*; and eastern oysters, *Crassostrea virginica*), culture method (oyster bags, *vs.* oyster cages *vs.* mussel lines), and depth to estimate potential overlap with eelgrass habitat, and ultimately infer the potential effects of aquaculture shading in the region.

Notable limitations

It is important to explicitly recognize that the available data only permit quantification of the spatial footprint of shellfish aquaculture, not the direct impacts of aquaculture on eelgrass presence, health, or productivity. The data presented in this Science Response Report (SRR) only address *potential* overlap between shellfish aquaculture and eelgrass habitat in the sGSL, and do not represent actual or observed effects. While we discuss *likely* impacts of shading based on the current knowledge, we do not provide empirical measurements of impacts to eelgrass. Such impacts are complex, nuanced, and difficult to quantify, least not due to the multiple traits of eelgrass that can be affected by aquaculture (e.g., areal coverage, canopy height, above- and belowground biomass, shoot density, physiology, etc.).

DFO Science Branch in the Gulf Region is currently working on satellite mapping of eelgrass habitat throughout the sGSL, which is expected to greatly increase knowledge of eelgrass distribution and spatiotemporal dynamics throughout the Gulf Region. It is expected that the results of these mapping efforts will have important implications for the management of aquaculture-environment interactions, and may require reassessment of the advice provided through the current process. While datasets derived from satellite mapping are not currently ready for publication, related insights have been added to this SRR where possible.

Shellfish aquaculture in the sGSL

In the sGSL, both oysters (*Crassostrea virginica*) and mussels (*Mytilus edulis*) are commonly farmed in nearshore waters (Bastien-Daigle et al. 2007; Filgueira et al. 2015). These bivalve species consume phytoplankton as a food source and thrive in highly productive coastal and estuarine environments such as those occurring throughout the sGSL. Most shellfish farming in this region takes place in sheltered lagoon-type systems that have relatively long residence times (Filgueira et al. 2015; Guyondet et al. 2013, 2015). A variety of different culture methods are used in the sGSL bivalve aquaculture industry, including bottom, off-bottom, and suspended culture methods for oysters, as well as suspended culture methods for mussels (Figure 2). The culture of additional species such as clams and scallops are licensed in some cases, though the quantity is unknown and considered to be very low.

For oysters, bottom culture has a long history in the region and consists of adding oysters directly to the benthos of leased areas in shallow subtidal waters where the oysters grow to market size and are subsequently collected using tongs and dredges (Medcof 1961). With off-bottom culture, oysters are held at a desired height in the water column in grow-out-bags that are affixed to metal rods anchored into the sediment in a table-like structure (Bastien-Daigle et al. 2007). These tables may be permanently attached to the bottom or removed seasonally (Bastien-Daigle et al. 2007). While bottom and off-bottom culture can affect eelgrass habitat, they are not the primary focus of this process. Bottom culture, though widespread in the sGSL, is not expected to result in shading of eelgrass, though there may be significant effects from harvesting (see “Physical Disturbances” section below). Off-bottom (i.e., “table” structures) can be very damaging to eelgrass as their spatially fixed nature causes permanent shading of the seafloor; however, these are uncommon in the sGSL and not currently expected to represent a significant risk to eelgrass at the regional scale (e.g., only one lease in NB contains off-bottom structures; see below).

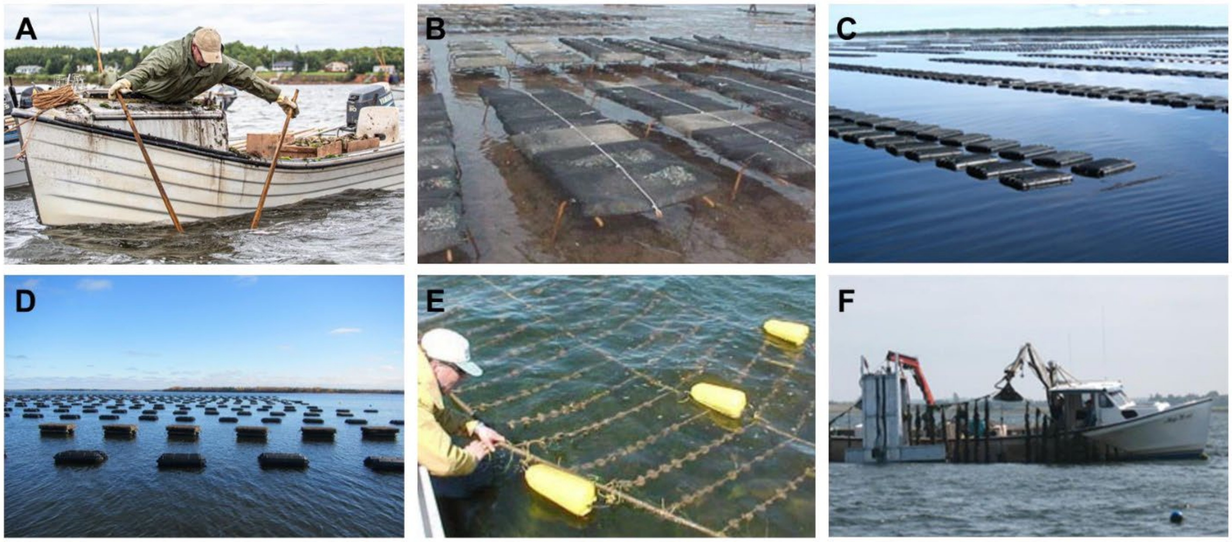

Figure 2. Images of various bivalve aquaculture methods in use in the southern Gulf of St. Lawrence, including: harvesting oysters using tongs in a bottom culture lease (**A**); off-bottom oyster tables (**B**); suspended oyster bags (**C**); suspended oyster cages; note the two orientations, flipped down for growth, flipped up for removing biofouling) (**D**); glued oyster lines (**E**); and longline mussel culture (**F**).*

*Figures taken from: A. Lufa Farms Inc.; B, E. Reference Manual For Oyster Aquaculturists; C, F. Canadian Aquaculture R&D Review 2009; D. DFO Gulf

While both bottom and suspended culturing methods are used for oysters, the majority of oyster farming in the sGSL employs suspended culture techniques. Therein, oysters are suspended at the surface (or just below the surface) in holding structures, which typically consist of either mesh bags, cages, or a series of ropes (Bastien-Daigle et al. 2007; Comeau 2013; Skinner et al. 2014). Floating bags and cages can also be arranged at different depths, though this is uncommon in the shallow coastal waters of the sGSL (Comeau et al. 2009). The holding structures are attached to a series of floats, connected linearly by rope, which are anchored to bottom on either side using concrete blocks or other anchoring mechanisms (Bastien-Daigle et al. 2007; Comeau 2013). The designs of suspended holding structures vary, with many products available from commercial suppliers. All suspended culture within the water column is allowed to move vertically and horizontally with tidal currents and changes in depth, whereas fixed off-bottom culture structures (i.e., tables) are anchored to the sediment and do not move with the tide (Bastien-Daigle et al. 2007). Allowing for slack in suspended lines reduces the force experienced on the lines and anchors, reducing the risk of losing gear during storms (which can itself pose risk to surrounding habitats; McKindsey et al. 2011), and also reduces localized effects of shading and bio-deposition by spreading these effects over a larger spatial area (Transport Canada 2007, Howarth et al. 2021).

Suspended bags and cages are the most prevalent oyster culture methods used in the sGSL. In New Brunswick either cages or bags are used on 149 out of 150 active suspended sites (see section “Spatial interactions between shellfish aquaculture and eelgrass” below). These gear types differ in several ways, although for eelgrass the most important aspects relate to their size and, by extension, the depth of water for which they are suitable. Bags are typically deployed on either side of a central anchored line with integrated floats, and have minimal spacing between bags, creating an essentially continuous floating structure along each line (Figure 2C and Appendix I). In contrast, cages are manufactured in several formats, but most typically hold 4 to 6 bags per cage arranged in a 2x2 or 2x3 form with floats attached above (Figure 2D and

Appendix I). Unlike bags, cages are typically interspersed with gaps of approximately 3 m along the anchored lines, likely allowing more light to reach the seafloor. Due to their low profile, bags are suitable for use in shallower water than cages; cages are presented as requiring ideally 2.5–4.5 m of water, while bags can be used in water depths less than 1 m. Both bags and cages are typically lowered to the seafloor in the winter to avoid ice, requiring either sufficient depth on-lease or specified overwintering locations.

In addition to the oyster culture methods described above, other types of gear may be currently in use or expected to grow in prevalence in the future. In particular, novel forms of suspended culture with different footprints than the typical suspended-bag and cage gear are being developed for use in the sGSL. These methods would be expected to affect light dynamics in a similar manner as current suspended gear types, though the extent and magnitude is not known and would require additional research and experimentation.

In contrast to oysters, cultured mussels in the sGSL are grown entirely on suspended longlines (Filgueira et al. 2015). Anchored on both sides of a back-line, sleeved mussels (i.e., “socks”) are suspended in the water column by a series of buoys and are arranged and suspended along 100–200 m longlines where they remain for 2–3 years to reach market size (Filgueira et al. 2015). To avoid winter ice and warm summer temperatures at the surface, lines are often sunk to a desired depth by removing floats or attaching weights.

Shellfish aquaculture differs between the three provinces that comprise the Gulf Region: New Brunswick (NB), Nova Scotia (NS), and Prince Edward Island (PE). Though similar in many respects, contextual differences in environmental conditions and histories result in different aquaculture practices at the provincial level. Additionally, management of aquaculture activities varies across jurisdictions, although this is beyond the scope of the current process.

While all forms of suspended culture occurring in shallow waters can potentially affect eelgrass habitat, it is important to note that direct interactions (i.e., shading, physical disturbance) with eelgrass in the sGSL is expected to be most common with oyster aquaculture, as mussel culture most commonly occurs in waters too deep for eelgrass. This is mostly due to the typical long-line culture method used in the Gulf Region, whereby mussel culture predominantly occurs at > 5 m depth (Drapeau 2006; A. Ramsay, PEI Dept. of Fisheries and Communities, pers. comm.), whereas the vast majority of eelgrass in aquaculture bays of the sGSL occurs in depths < 3 m (see section *Spatial interactions between shellfish aquaculture and eelgrass* below).

Likely effects of shellfish aquaculture on eelgrass in the sGSL

Shellfish aquaculture has the potential to have positive, negative, and neutral effects on eelgrass through a number of pathways (Table 1). The ways in which shellfish aquaculture can affect eelgrass have recently been reviewed by Howarth et al. (2022). Generally speaking, shading, direct physical disturbance, and the filtration and deposition activities of cultured bivalves can impact eelgrass in various ways. When considering overall impacts of aquaculture on eelgrass, it is thus important to consider the net effects of the different pathways, which will depend on localized baseline conditions. It is also important to recognize that impacts are not consistent for different eelgrass traits; while some traits may be negatively affected by aquaculture, others may be positively affected at the same time. As such, quantifying the “impact” of shellfish aquaculture to the eelgrass itself is complex and nuanced. The focus of the current process is on alterations to the light regime caused by the presence of aquaculture gear. Information about other pathways is summarized below; for further information, consult the cited references.

Many of the negative effects of aquaculture on eelgrass can be prevented or mitigated through various approaches to lease siting, culture practices, and management. While these are beyond the scope of the present process, notable examples will be cited where possible. Most importantly, spatial avoidance of eelgrass habitat, where possible, appears to be the most effective method of mitigation, and is a common approach used by federal and provincial management regimes across the Gulf Region (e.g., New Brunswick's "Bay Management Framework" approach; Howarth et al. 2021).

Table 1. Pathways of interaction between eelgrass and bivalve aquaculture in sGSL and expected direction of response (+, Positive; -, Negative) to eelgrass populations. Red = Negative, Yellow = context-dependent , Green = positive. Note that the spatial scale and extent of each interaction is variable, ranging from local (i.e., gear footprint) to lease- and bay-scale. The magnitude of effect for each particular interaction is not considered.

Expected Interaction Pathway (*scale*)	**Benthic Oyster Culture**	**Oyster Table Culture**	**Suspended Oyster Culture**	**Mussel Culture**	**Further Reading**
Shading from structures *(local scale)*	N/A	-	N/A if no overlap, - if overlap	N/A if no overlap, - if overlap	McKindsey et al. (2011) Skinner et al. (2014) Wong et al. (2021) Howarth et al. (2022)
Organic Matter deposition *(lease scale)*	+ in oligotrophic, - in eutrophic	+ in oligotrophic, - in eutrophic	+ in oligotrophic, - in eutrophic	+ in oligotrophic, - in eutrophic	Wicks et al. (2009) Borum et al. (2014) Castorani et al. (2015) Oreska et al. (2021)
Nutrient excretion *(variable scale)*	+ in oligotrophic, - in eutrophic	+ in oligotrophic, - in eutrophic	+ in oligotrophic, - in eutrophic	+ in oligotrophic, - in eutrophic	Valiela et al. (1997) Alexandre et al. (2015) Castorani et al. (2015) Sandoval-Gil et al. (2016)
Phytoplankton depletion and filtering *(bay scale)*	+	+	+	+	Newell and Koch (2004) Ibarra et al. (2012) Guyondet et al. (2013) Smith et al. (2018)
Invasive epifauna *(variable scale)*	-	-	-	-	McKindsey et al. (2011) Wong and Vercaemer (2012) Carman et al. (2019) Murphy et al. (2019)
Mechanical disturbance7 *(local to lease scale)*	-	-	-	-	DFO (2012) Orth et al. (2017)
Water flow reduction and wave attenuation (*variable scale*)	+ sheltering	+ in high energy systems, - in low energy systems	+ in high energy systems, - in low energy systems	+ in high energy systems, - in low energy systems	Newell and Koch (2004) Wicks et al. (2009) McKindsey et al. (2011) Uhrin and Turner (2018)

Shading

Oysters

Shading is thought to be a major mechanism in which oyster aquaculture negatively affects eelgrass (Skinner et al. 2013). This shading can be due to the aquaculture gear itself, the presence of animals within the gear, and/or fouling organisms on the outside of the gear

(Robertson and Mann 1984; Wong and Vercaemer 2012; Skinner et al. 2013). Globally, it is estimated that shading (i.e., reduction in available light) from oyster aquaculture can negatively affect eelgrass, although effects vary by context and method. For example, a global meta-analysis found that shading from suspended and off-bottom oyster aquaculture methods (but not on-bottom methods) can negatively impact eelgrass density, growth, and reproduction (Ferriss et al. 2019). All maritime Canadian shading experiments have shown losses in eelgrass coverage (Robertson and Mann 1984; Skinner et al. 2013; 2014). Studies in the sGSL are among a handful of investigations directed at oyster shading from suspended culture (Skinner et al. 2013; 2014; Howarth et al. 2022).

The issue of oyster aquaculture-eelgrass shading interactions in the sGSL was first described by the work of Skinner and colleagues. Across three bays in northern NB, Skinner et al. (2013) found that aboveground biomass, shoot density, and canopy height were reduced beneath suspended oyster operations as compared to reference sites 300 m away. A significant reduction in photosynthetic capacity suggested that shading may have played a major role in such effects (Skinner et al. 2013). This hypothesis was further supported by experimental shading manipulations which significantly reduced eelgrass shoot density, above- and belowground biomass, canopy height, leaf size, and photosynthetic capacity after 67 days at 26% subsurface irradiance (Skinner et al. 2014). Outside of the sGSL, low eelgrass survival is a common feature of shading studies (Eriander et al. 2017; Wong et al. 2021). Eelgrass seedling survival in shaded *vs.* unshaded plots in NS were ~35% and ~50% respectively (Robertson and Mann 1984). Likewise, Sandoval-Gil et al. (2016) noted an absence of eelgrass under floating Pacific oyster aquaculture.

While it has been demonstrated that oyster aquaculture has the potential to negatively affect eelgrass in the sGSL, there are a number of complexities that need to be considered. These include distance from a given lease, stocking density, water depth, gear type and culture methods, the potential for eelgrass recovery, and potential positive effects of filtration on water clarity. For example, the impacts of shading reported in Skinner et al. (2013) were largely restricted to a 25 m radius from the farm and impacts sharply dissipated with increasing distances from leases. Similarly, across five bays in NB, comparisons between eelgrass within suspended oyster leases and eelgrass 300 m away were highly variable for coverage and productivity metrics; however, above-ground biomass and leaf productivity were lower under culture. The variable response between sites indicates that localized conditions, such as nitrogen loads (McIver et al. 2019), can influence the magnitude of effects from oyster culture (Skinner et al. 2013). Skinner et al. (2014) found no significant effect of oyster stocking density on light, suggesting that shading is caused entirely by gear and is not affected by the quantity or biomass of cultured oysters present. Contextually, these studies also were conducted on suspended bag oyster aquaculture in very shallow water (0.3–0.6 m), which likely represents the worst-case scenario in terms of shading, as will be detailed in sections below.

Different suspended oyster culture methods can also influence the relative amount of eelgrass shading in the sGSL. Skinner et al. (2014) experimentally suspended oyster shells on top of an existing eelgrass bed in Bay St. Simon, NB using two culture methods: 1) glued oyster strings; and 2) floating oyster bags with and without an additional light-capturing screen to simulate high stocking density. They subsequently tracked light and eelgrass productivity for ~ 1 year for comparison to a control site with no suspended oysters. Control eelgrass beds with no suspended oysters received 60% of subsurface irradiance, while strings received 43% and bags received 26%. Reduced photosynthetic rates with increasing shading were apparent. After 67 days, there were no differences in canopy height between treatments, and only shoot density and aboveground biomass were reduced in the most extreme shading treatment. However, by the end of the experiment, all endpoints for eelgrass under the two suspended bag treatments were significantly lower than the control; oyster strings showed no reduction in cover, height, or biomass (Skinner et al. 2014).

Eelgrass recovery following the removal of oyster aquaculture gear can also be influenced by shading. Herein, the long-term effects of stem die-off have been investigated for a number of oyster aquaculture shading studies (Skinner et al. 2013; 2014). Carbohydrate reserves built during the growing season support survival of eelgrass through the winter (Burke et al. 1996). The bulk of eelgrass productivity may not extend past July in the sGSL; thus, shading during this growth period is likely detrimental to energy storage as photosynthesis is impaired (Burke et al. 1996; Ochieng et al. 2010; Clausen et al. 2014). Recovery through clonal growth is also relatively slow, with growth rates of perennial rhizomes averaging 15 cm per year in United States investigations (e.g., Olesen and Sand-Jensen 1994), although annual plants may re-establish rapidly (Robertson and Mann 1984).

While direct shading can have negative effects on eelgrass, it is important to note here that the filtration capacity of bivalves may positively affect eelgrass. It is well documented that the filtration activity of bivalves can enhance water clarity and remove excess nutrients from coastal waters. Increasing filter feeder abundances have been shown to enhance water clarity in coastal systems (Meeuwig et al. 1998; Lefcheck et al. 2018). Indeed, filtration associated with bivalve (mussel) aquaculture has been shown to decrease seston levels in coastal sGSL surface waters (Meeuwig et al. 1998; Comeau et al. 2015; Guyondet et al. 2015), although studies explicitly with oysters are lacking. Furthermore, bivalve harvesting can help remove excess nutrients in coastal waters of the sGSL (Clements & Comeau 2019), although the net effect and extent of such harvesting on nutrient levels and eutrophication depends on bay-scale conditions and remains speculative. Studies also suggest that increased filtration associated with bivalve aquaculture can help reduce epiphytes (Smith et al. 2018) that can negatively affect eelgrass (Coffin et al. 2018; DFO 2021).

Mussels

Mussel culture in the sGSL is not expected to directly shade eelgrass due to differences in depth limitations of the two production systems as previously mentioned. The shading from aquaculture structures (e.g., mussel lines and floats/buoys) in the aquatic environment is dependent on the proximity and angle of the structure capturing light. However, no exact recorded distances between mussel lines and eelgrass beds are available. Neither van den Heuvel et al. (2019) nor Murphy et al. (2019) differentiated between mussels or oysters in respect to bivalve aquaculture linkages with eelgrass in the sGSL. Other aspects of mussel production may also affect light dynamics indirectly (e.g., filtration, sedimentation/ biodeposition).

Mussel or oyster aquaculture material may move into eelgrass beds unintentionally. For example, estimated mussel aquaculture material in Tracadie Bay PEI includes 60,000 mussel anchors and buoys and 150 km of rope (McKindsey et al. 2011). As any material that absorbs light can shade eelgrass, aquaculture litter may be an additional source of eelgrass shading. Shading effects of litter can be further compounded by the accumulation of biofouling species. Indeed, bivalve aquaculture gear is a known substrate for biofoulers such as invasive tunicates (Wong and Vercaemer 2012; Murphy et al. 2019); these species also have the potential to adhere directly to eelgrass (Carman et al. 2019). However, quantitative estimates of aquaculture litter and any associated shading effects are unavailable in the sGSL.

Direct physical disturbance

Aside from the indirect effects of shading (i.e., the primary focus of this review), shellfish aquaculture can affect eelgrass habitat through direct physical disturbance. This can occur through multiple pathways and at different stages and can be moderated or exacerbated by environmental conditions such as depth and tidal range. Direct physical contact with aquaculture gear or related structures can potentially damage both above- and below-ground components of eelgrass, and the effects can range from transitory to semi-permanent.

Most directly, eelgrass habitat can be damaged through the installation of gear structures such as anchors used to secure suspended lines. These anchors typically consist of concrete blocks or metal screw-anchors applied to either end of each line of gear. Though the extent of this interaction is limited, displacement of vegetation can be caused by installation of these structures, which can persist if gear remains in place. To mitigate these effects when avoidance is not possible, best practices include proper sizing of anchors for local conditions and culture practices and the installation during winter months where possible (Transport Canada 2007). Off-bottom gear structures (e.g., tables) can be expected to cause similar damage as gear anchored in a fixed position.

Direct disturbance of eelgrass can also result from gear contact with the seabed or plant canopy. The likelihood and severity of this type of disturbance depends on factors such as water depth, tidal range, gear floatation, duration of impact, and degree of slack in the suspended lines. Contact with the seafloor is typically avoided whenever possible due to negative effects on the shellfish themselves (e.g., resuspension of sediments, exposure to benthic predators), but can occur particularly in very shallow areas and at very low tides. Contact can be particularly damaging if the suspended lines allow for movement while near to the seabed, leading to a scouring effect that can dislodge rhizomes; this can occur from both gear units themselves (e.g., bags or cages) as well as suspension lines and buoys, increasing the footprint of the potential impact. Finally, oyster bags or cages set on top of the sediment during overwintering can potentially impact eelgrass where it may be present through direct disturbance as well as sediment compaction and smothering (Bastien-Daigle et al. 2007).

In addition to direct physical disturbance from aquaculture gear, eelgrass habitat can potentially be affected by direct contact associated with harvesting practices. While not the focus of the current process, this may be particularly relevant for bottom-culture conducted without the use of gear, as shellfish harvesting is commonly conducted either with tongs, dredges, or other suction/pressure-based technologies that can cause significant disturbance to the benthos (Ferriss et al. 2019). For suspended culture, physical disturbance associated with harvest occurs when boats used by aquaculturists contact the seafloor or the plant canopy, either with the vessel hull or propeller (Orth et al. 2017). Impacts can also occur when gear is moved to shore for processing either by hand/wading, or mechanically with the use of ATVs or tractors. Propeller scarring in eelgrass beds is readily apparent in shallow waters across the Gulf Region, both within and outside of aquaculture areas (DFO Gulf, unpublished data); notably this type of disturbance is not restricted to vessels conducting aquaculture.

Bivalve activity – deposition and filtration

Algal shading of rooted aquatic vegetation is common as a result of high levels of nutrients (typically nitrogen) inducing macroalgae- or phytoplankton-dominated states in coastal waters (Valiela et al. 1997; DFO 2021). As such, the biological processes associated with bivalve aquaculture, such as deposition and filtration, that stimulate and/or remove phytoplankton and other seston from coastal waters can contribute to eelgrass impacts. Bivalves excrete ammonium and particulate organic matter in the form of feces and pseudofeces, both of which contribute to coastal nutrient pools (Guyondet et al. 2010; Jansen et al. 2018). This nutrient release can stimulate phytoplankton production; however, eelgrass may also use these nutrients (Reusch et. al. 1994; Sandoval-Gil et al. 2016; Jansen et al. 2018). Bivalves release ammonium – the preferred form of nitrogen for eelgrass growth (Reusch et. al. 1994; Alexandre et al. 2015). As such, bivalves have the potential to stimulate eelgrass production under certain conditions; however, increases in phytoplankton associated with nutrient excretion can have the opposite effect. Eelgrass adjacent to Pacific oyster off-bottom aquaculture tended to have larger leaves and faster growth rates compared to reference areas; however, these larger, faster-growing eelgrass beds had lower densities than reference areas, and eelgrass was completely absent below oyster structures (Sandoval-Gil et al. 2016).

Shellfish deposits directly add organic matter to sediments and can result in adverse effects to eelgrass, namely in the form of sulfide stress (Hargrave et al. 2008; Hasler-Sheetal et al. 2016). These effects only occur in depositional areas where organic matter can accumulate, which is driven by hydrodynamic conditions. For example, when nitrogen is not limiting for eelgrass growth, mussel aquaculture deposits can increase overall sediment oxygen demand resulting in increased sulfide tissue incursion and reduced carbohydrate reserves in eelgrass (Castorani et al. 2015; Hasler-Sheetal et al. 2016). In the sGSL, high levels of organic matter can accumulate under mussel lines and increase porewater sulfide concentrations (Callier et al. 2007; Hargrave et al. 2008). Beneath mussel leases in Tracadie Bay, PEI, sediment organic matter can range from 3.4–18.3%, whereas eelgrass beds in the same bay display organic matter ranges of 0.6–2.8% (Hargrave et al. 2008). Skinner et al. (2013) found no differences in sediment organic matter in oyster leases with eelgrass compared to eelgrass sites 300 m away. Eelgrass may exist in sediments up to 17% organic matter in the sGSL; however, increasing plant stress occurs above 4% (Wicks et al. 2009; Coffin et al. 2018). While bivalves reallocate water column nutrients for eelgrass growth, excess deposits are potentially detrimental to eelgrass survival within the immediate vicinity of aquaculture structures, particularly in depositional environments (Castorani et al. 2015; Sandoval-Gil et al. 2016; Jansen et al. 2018).

It is important to note that the net contributions of bivalve deposition and filtration need to be accounted for when considering impacts on eelgrass. For example, light availability can help mitigate many negative effects of organic matter over-enrichment (e.g., Castorani et al. 2015) and filtration of turbid water may conversely balance light availability (Newell and Koch 2004; Ibarra et al. 2012). Since these two processes tend to have contrasting effects on eelgrass, it is important to account for the relative impact magnitude of both deposition and filtration when assessing impacts on eelgrass.

Effects of suspended aquaculture on light (experiment)

The effect on underwater light conditions of oyster cage culture gear was tested through two field experiments in Cocagne Bay, NB in late summer and fall 2021. Both experiments were conducted at the same site (utilizing suspended oyster cages) and compared light availability in the farm and at a reference station located 100 m to the north where there was no aquaculture. The rationale for conducting these experiments was to provide data regarding light penetration beneath an oyster aquaculture lease that is more representative of current oyster culture practices (i.e., oyster cages), as compared to previous studies focusing on suspended bag culture in very shallow water (Skinner et al. 2013, 2014).

The first experiment compared light levels on the bottom of the bay within and outside the farm, using 11 photosynthetically active radiation (PAR) sensors arranged in a cross pattern to cover both under and between cage line locations, and the bottom reference station equipped with two of the same PAR sensors. A PAR sensor was also deployed immediately below the sea surface at the reference station to allow for measurement of background light attenuation through the water column. During this first experiment light conditions at all stations were monitored for 7 days. The second experiment aimed at capturing the light availability at various depths directly under the farm structures. The same reference station configuration was repeated to provide control light conditions and attenuation. In the farm, replicate PAR sensors were hung directly below the center of individual oyster cages at three distances (approximately 0.1, 0.5, and 1 m) to measure light availability as a function of distance. For this second experiment sensors were left to record for 24 h to avoid fouling and deposition bias and risk of damaging the sensors hanging under the cages. For further details on the methodology, please refer to Appendix II.

Light measurements beneath standard oyster cages indicated that light is severely reduced immediately below the cages up to distances of approximately 1 m (Figure 3). This finding supports that of Skinner et al. (2014), as they measured light to be approximately 26% of subsurface intensity at eelgrass canopy underneath oyster bags in water depth of 0.6 m (referenced to chart datum). While light levels beneath oyster cages at the deepest depths we measured (2.5 m) were lower than control light levels, we found that differences in daily integrated light (i.e., PAR accumulated over 24 h) beneath cages and in the control plots were not drastically different after depths of approximately 2 m. This suggests that if oyster cages are placed in areas where distance to the eelgrass canopy is at least 2 m, the cages should not have a substantial impact on eelgrass with respect to light. However, cages placed in shallower water may still cause significant shading effects.

Given that the majority of shellfish aquaculture in the sGSL occurs at depths > 2 m (see “spatial interactions” section below), our results suggest a limited shading impact at the regional scale. It is important to recognize that our experiment was conducted in a single bay at a single oyster farm under one type of oyster aquaculture gear. Although these results generally support our conclusions, further experiments repeating our approach with greater depth resolution in different bays and beneath different types of aquaculture gear would provide a more precise and holistic understanding of suspended aquaculture effects on light attenuation and, by extension, eelgrass.

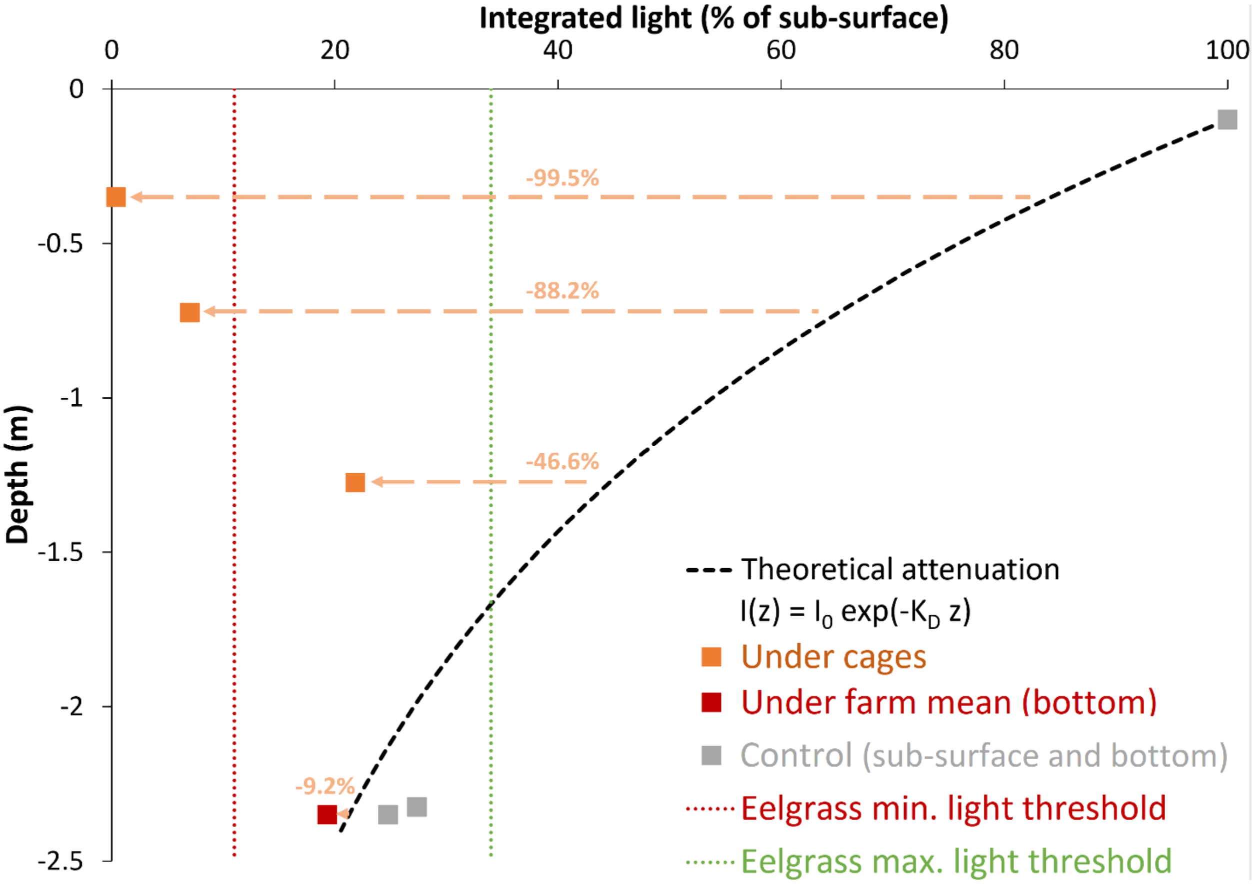

Figure 3. Integrated light under oyster cages and at the bottom of farm and control stations expressed as a percentage of sub-surface light. The Beer-Lambert law for the empirically measured diffuse attenuation coefficient (K_D) is also shown as well as the light thresholds for eelgrass reported in the literature: 11% as the lowest value that could support eelgrass (Olesen and Sand-Jensen 1993) and 34% where eelgrass can be light-limited (Ochieng et al. 2010).

Spatial interactions between shellfish aquaculture and eelgrass

To estimate the potential scale of shading effects from suspended shellfish aquaculture on eelgrass habitat, spatial analyses were conducted using Geographic Information Systems (GIS) tools to determine the overlap between aquaculture leases and potential eelgrass habitat. Efforts to understand the spatial footprint of overlap between shellfish aquaculture and eelgrass habitat are hampered by data availability representing both aquaculture operations and the distribution of eelgrass in the sGSL. For this report, best available data representing aquaculture leases and gear utilization were collected from the provincial (NB, NS) and federal (PE) departments responsible for aquaculture in the respective jurisdictions (Table 2). The specificity, age, and quality of data varied across and within provinces, mirroring the varied state of development of shellfish aquaculture in the region. Generally, the data received included non-comprehensive information regarding the location and size of leased areas, type of culture (i.e., bottom, off-bottom, suspended), and expected utilization. In some cases, counts of gear presence (i.e., number of lines, number of culture units, etc.) were available. Additional estimates of gear usage were provided from publicly available site development plans as well as satellite imagery and orthophotos present in DFO-Science databases. Descriptions of the datasets used in the analyses below are shown in Table 2.

Table 2. Datasets and sources used for GIS analyses of shellfish aquaculture.

Province	Dataset	Source	Level of Detail
NB	GIS shellfish aquaculture leases as of 2023	NB Department of Agriculture, Aquaculture and Fisheries (see also MASMP)	Outlines (Leased, Vacant, Under review, Rejected, Overwintering)
NB	GIS suspended lease data 2022	NB Department of Agriculture, Aquaculture and Fisheries	Outlines, bag equivalents for all active leases (counted 2022)
NS	GIS leases as of 2019	NS Department of Fisheries and Aquaculture	Outlines, type culture, species
NS	GIS leases as of 2023	NS Department of Fisheries and Aquaculture (see also NS Site Mapping Tool)	Outlines, species
NS	Table of max cages	NS Department of Fisheries and Aquaculture	Maximum number cages per county
PEI	GIS leases as of 2022	DFO-PEI Aquaculture Leasing Division	Outlines, species
PEI	GIS site development plans (polygon)	DFO-PEI Aquaculture Leasing Division	Portions of leases, for some leases–max lines, bags, cages, racks, spat
PEI	Table bag counts 2021	DFO-PEI Aquaculture Leasing Division	Bag count (assumed 6-bag cages unless other data overlapped)

For eelgrass distribution, comprehensive maps at the scale of the Gulf Region do not currently exist, though efforts are underway to develop eelgrass maps using satellite imagery across the sGSL (Monica Boudreau, DFO-MPC, pers. comm.). Developing robust mapping and monitoring capabilities is recognized as a critical need for the management of coastal activities that may affect eelgrass habitat (Barrell et al. 2015). Notably, ongoing review of satellite imagery has detected large-scale interannual changes in eelgrass habitat that were previously unknown in several bays throughout the region, indicating that eelgrass dynamics may be undergoing changes that could greatly affect the advice provided in this process. Greater efforts towards detecting and understanding change in eelgrass distribution are needed to provide high-quality advice to management on aquaculture-eelgrass interactions. In the absence of detailed eelgrass habitat data, the overlap analysis below is presented in terms of *potential* interactions with eelgrass habitat, rather than quantifying *actual* interactions occurring in known eelgrass beds.

Additional supporting data included bathymetric maps of aquaculture areas derived from acoustic data collected by DFO Science in conjunction with the DFO Marine Planning and Conservation (MPC) sector. These acoustic datasets are also used for mapping eelgrass distribution (e.g., Barrell and Grant 2013), and allowed for the identification of maximum depth limits of eelgrass occurrence across dozens of aquaculture bays in the Gulf Region.

Published literature suggests that the proportion of available eelgrass habitat that directly overlaps bivalve aquaculture in sGSL estuaries is relatively low. For example, van den Heuvel et al. (2019) found using boat-based sonar that the area of available eelgrass habitat under bivalve aquaculture ranged from 0.03% to 6.28% of available eelgrass habitat across 16 sGSL estuaries. Oyster culture is the primary practice in the sGSL that can overlap with eelgrass, as it can be practiced at less than 3 m; whereas mussels are typically grown at depths of 5 m or greater (Drapeau 2006; A. Ramsay, PEI Dept. of Fisheries and Communities, pers. comm.).

Thus oyster aquaculture in the sGSL is more likely to directly interact with eelgrass through mechanisms like shading (Skinner et al. 2013; Boudreau and Landry (2016, PARR-2015-G-04). Accordingly, oyster aquaculture will be the primary focus for the analysis below.

Shellfish aquaculture in the sGSL

Data representing the shellfish aquaculture leases and gear usage varies across the jurisdictions present in the sGSL. Many unknowns exist, requiring several assumptions for the analysis below. In particular, suspended leases in all three provinces are commonly authorized for multiple species (particularly oysters and mussels), and production levels of each at the lease-scale are not known. Detailed information about species or gear present will be integrated where possible; otherwise, inferences were made regarding the species being cultured based on physical context and what is known of operations by province. The proportion of leases currently active was only known for NB; accordingly, information presented below about NB represents active leases, while PE and NS reflect all leases. In all cases, the most recent and best available data were used whenever possible (Table 2).

There are notable differences in the terminology used for different culture methods across jurisdictions in the sGSL. Prince Edward Island categorizes its leases as either bottom (i.e., without gear, mostly oyster), off-bottom, or surface. Off-bottom represents suspended oyster leases, while surface represents either suspended oyster or mussel culture. To our knowledge, no fixed table-like structures are used in PEI. For New Brunswick, leases are categorized as bottom, overwintering, or suspended. Overwintering leases represent areas where gear is sunk to avoid winter ice, resulting in gear on the bottom over the winter months. Suspended leases accounted for all other types of culture, including one lease utilizing fixed tables. In Nova Scotia, leases are categorized as either bottom without gear, bottom with gear, or suspended culture.

The quantity and type (i.e., species, gear) of shellfish aquaculture varies across the sGSL and between the three provinces comprising the study area:

Prince Edward Island

Prince Edward Island contains the largest number of combined surface (323) and off-bottom (356) leases and leased area (5641.2 hectares (ha)), with an additional 788 bottom leases without gear. All of the off-bottom leases are authorized for oyster culture, and 88 of the 323 surface leases also allow oyster culture, for a total of 444 oyster leases. In sum, the total leased area authorized for oyster culture in PEI covers 2065.2 ha. The remainder, which comprises the majority of leased area on PEI, is devoted to mussel culture. Information on gear type from counts in 2021 and from site development plans was available for a subset of 261 leases (58.8% of 444 authorized oyster leases). These data identified the primary gear unit in use as well as additional gear types for leases with multiple types of gear. Of the 261 leases, 198 (75.9%) primarily used 6-bag cages, 43 (16.5%) used 4-bag cages, 17 (6.5%) used single suspended bags, and 10 (3.8%) used primarily 2-bag cages. Available information also indicated that 17 leases used multiple types of gear: 12 used a mix of bags and cages, and 5 used multiple cage sizes. For leases that had bag data but no indication of culture type (e.g., single-bag, cage size), a 6-bag cage was assumed so as to provide a maximum potential cage coverage area.

Nova Scotia

Nova Scotia has comparatively few suspended leases in the sGSL; based on 2019 data with detail on type of culture, sGSL NS contained 15 suspended leases authorized for oyster culture (349.3 ha), 28 bottom leases without gear (351.8 ha), and 3 bottom with gear leases (36.7 ha).

Though oyster culture in sGSL NS sometimes utilizes 4-bag cages, it is typically 6-bag cages that are used. Data provided by NS Department of Fisheries and Aquaculture presumed 6-bag cage for all sites. Other methods may be in use in small areas, and can be expected to increase in prevalence; for example, multiple sites are currently proposed that would use a different cage design (NS DFA, pers. comm.).

New Brunswick

In New Brunswick, 276 out of 782 shellfish leases in the sGSL are authorized for suspended culture, with the remainder representing bottom culture. According to gear counts from late summer 2022, 150 of these sites contained gear and 126 were considered inactive. The vast majority of suspended sites in NB grow oysters, with very few (< 5) growing mussels, representing little to no production (Joseph Labelle, Province of NB, pers. comm.). Oysters in NB are mostly cultured using cages or suspended bags, sometimes with both methods in a single lease (Table 3). A third method involving oysters glued individually to ropes also occurs in conjunction with other suspended methods in a limited number of leases (16/150 active sites). Lastly, one lease utilizes off-bottom tables. As glued oysters and tables represent a small fraction of active sites, these methods will not be of primary focus in the shading analysis below. Notably, experiments conducted by Skinner et al. (2014) found that the glued oyster method did not negatively impact metrics of eelgrass productivity.

Table 3. Active suspended leases in New Brunswick by gear type with gear quantities in terms of bag-equivalents; from summer 2022 gear survey. Source: Province of New Brunswick.

Method	Number of Leases	Bag-equivalents (BE)	Percent of total BE
Cages	83	464,392	76.27
Bags	44	73,538	12.08
Bags & Glued	15	52,839	8.68
Cages & Bags	6	13,042	2.14
Tables	1	4,494	0.74
Cages & Bags & Glued	1	600	0.10
Total	***150***	***608,905***	***100***

The total quantity of suspended gear deployed in NB was provided in terms of “bag-equivalents”, which was quantified based on standard oyster bag sizes; oyster cages typically contain 4–6 bags. For the purposes of the calculations below, it was assumed that leases with cages used the common 6-bag format, implying that six bag-equivalents equal one cage. For glued oysters, 150 oysters were considered equivalent to one bag in the source dataset provided by the Province of NB. This information was summarized over aquaculture management area (AMA) polygons provided by the Province of NB in order to ensure the privacy of growers. Each AMA is roughly equivalent to a bay unit in extent. Suspended shellfish aquaculture gear was present in 11 AMAs along the sGSL coast of NB. In total, active suspended leases covered 866.8 ha, or 2.8% of the area of the AMAs in which they occur. These active leases contained a total of 608,905 bag-equivalents, with the majority in cages (Table 3).

Overlap with potential eelgrass habitat

For the purposes of this analysis, potential eelgrass habitat was defined strictly by depth, with a maximum threshold of 3 m below mean tide as determined from acoustic mapping across the sGSL (Table 4). Acoustic mapping across several sites found that on average 98.01% of eelgrass in each bay occurred in depths less than 3 m, with a notable exception of Merigomish (NS) where 86.3% occurred below this threshold. This value is consistent with other published studies in the sGSL (e.g., van den Heuvel et al. 2019). The mean percent of eelgrass occurring below 2 m depth was calculated at 81.94%, implying that while most eelgrass occurs in very shallow waters, the 2–3 m range is nonetheless suitable habitat for eelgrass in most bays.

Table 4. Distribution of eelgrass by depth in a selection of sGSL bays, as determined by acoustic mapping conducted by DFO and partners.

Site	Province	Year	% Eelgrass < 3 m	% Eelgrass < 2 m
Bouctouche	NB	2020	99.7%	82.5%
Boughton	PE	2018	90.8%	72.6%
Cocagne	NB	2019	99.9%	86.8%
Foxley/Trout	PE	2020	100.0%	98.3%
Merigomish	NS	2016	86.3%	41.6%
St-Simon	NB	2021	96.7%	65.0%
Richibucto	NB	2020	99.9%	92.5%
Pugwash	NS	2019	97.3%	95.2%
Kouchibouguacis	NB	2019	99.8%	99.3%
Tabusintac	NB	2020	99.8%	99.0%
Covehead	PE	2018	99.7%	85.3%
Hunter River	PE	2019	99.5%	93.7%
Grande Digue	NB	2020	100.0%	98.1%
Grande Digue	NB	2021	100.0%	60.2%
Dunk	PE	2019	99.8%	66.6%
Southwest River	PE	2018	99.0%	74.3%

Site	Province	Year	% Eelgrass < 3 m	% Eelgrass < 2 m
Mean			***98.01%***	***81.94%***

Some areas of the sGSL shallower than 3 m of depth will not be suitable for eelgrass, especially due to ice (e.g., van den Huevel et al. 2019), and some eelgrass will occur in areas deeper than 3 m, though available data suggest this is rare in aquaculture bays of the sGSL (Table 4). Accordingly, these estimates should be viewed as near the maximum possible overlap of footprint, assuming that eelgrass occurs in all areas with suitable depths.

With respect to culture units, accurate estimates of the shading footprint could only be provided for areas with data representing gear utilization. In practice, this information represents a snapshot of gear present at a particular time. This may or may not be representative of actual utilization throughout the year, and similarly may or may not reflect culture practices in a “typical” year. As such, these can only be regarded as rough estimates.

Shading caused by culture units is complex, and requires several assumptions and considerations. Some of this is addressed in the light experiment discussed above. In general, the amount of light reaching the seafloor (or eelgrass canopy) is primarily a function of solar insolation (i.e., the amount of incident solar radiation per unit area and time) and interactions with the air-water interface and the water column, including any obstructions such as aquaculture gear. All of these factors are temporally and spatially variable, and precise estimation and modeling of these characteristics is beyond the scope of the current process. The approach taken here was to quantify the horizontal area of gear expected to cause shading in order to scale the potential results.

To conduct this analysis, the spatial dimensions of common bag and cage culture units were estimated from Comeau (2013). Typical oyster bags (i.e., Figure 2C and Appendix I) were approximated at 45.7 cm x 88.9 cm (0.41 m^2) and 6-bag oyster cages as 147.3 cm x 91.4 cm (1.35 m^2). For cages of other sizes, it was assumed that 3-bag cages had the same horizontal footprint as 6-bag cages, as they are arranged in a 3x1 format. Cages with 4 and 2 bags (i.e., 2x2 and 2x1 arrangements) were assumed to have horizontal footprints with the same width and ⅔ of the length of 6-bag units (Table 5). Note that in practice, there may be variance in the size of some culture units, for example due to the size of floats used with oyster bags, and the extent to which non-standard sizes of cages and bags are used is not known. Further, the shading footprint of spat collectors was not investigated.

Table 5. Dimensions of typical oyster aquaculture gear units used for determining the spatial footprint of shading; adapted from Comeau (2013).

Gear unit	Length (cm)	Width (cm)	Area (m^2)
Bag	88.9	45.7	0.41
6- and 3-bag cage	147.3	91.4	1.35
4- and 2-bag cage	98.2	91.4	0.898

Other shading considerations

The analysis presented below did not account for the effects of other aspects of shellfish culture on shading dynamics. In particular, the aggregation of culture units has important implications for shading. Suspended bags are typically deployed to either side of a central line (i.e., Figure 2C and Appendix I), which could be expected to create a larger shading footprint than if the same quantity of culture units were dispersed. In contrast, cage units are typically spaced roughly every 3 m along the central line, theoretically allowing more light to pass around the culture units. For both methods, sufficient distance is left between lines to allow for access, typically 5–9 m (Comeau 2013). The total quantity of cultured shellfish per lease is limited by the production carrying capacity; any changes to carrying capacity could be expected to result in correspondingly more or fewer oysters, with potential implications for shading.

Prince Edward Island

Detailed data representing gear types and quantities for PEI were reviewed for four aquaculture bays (Boughton, Covehead, Hunter River, and Foxley-Trout River). Gear counts from these bays were used to estimate gear types and densities across all PEI aquaculture bays. Assuming that all suspended and off-bottom leases across the province with oyster listed as a farmed species (sum of 2,065.2 ha) contained the same distribution of gear types as the sample bays explored in detail, the average percentage of gear cover within-lease was estimated at 3.31% based on 2021 bag counts. This makes the gear coverage and shading (regardless of depth) about 68.4 ha for PEI.

Based on the acoustic-derived depth data in these four aquaculture bays, there was an average of 1.5% of the suspended lease area in the < 3 m zone defined as potential eelgrass habitat. If we assume a similar average depth distribution for the rest of the applicable PEI leases (2,065.2 ha of which 3.31% is directly shaded), the result is approximately 1.03 ha of potential eelgrass shading from suspended oyster aquaculture in PEI.

These numbers can only be considered rough estimates due to the assumptions required in extrapolating data from four bays to the entire province, and uncertainty around which species are cultivated in surface leases authorized for both oysters and mussels. PEI's mussel culture industry is well-developed, taking advantage of deeper waters more common in sGSL PEI than NB and NS. As many suspended leases are transitioning from mussel to oyster culture (Clements & Comeau 2019), the depth distribution of PEI oyster culture correspondingly is much deeper than in the other provinces of the sGSL, resulting in relatively little overlap with potential eelgrass habitat despite the size and spatial extent of the industry.

New Brunswick

The footprint of shading from aquaculture gear in NB occurred in suspended leases covering a total of 866.8 ha. Accounting for variability in gear types required several assumptions. In particular, 22 of the 150 active leases were recorded as using multiple methods (Table 3). For the 15 leases using bags and glued oysters, all bag-equivalent information was translated to bags to estimate gear coverage and shading. Similarly, the 6 leases utilizing both cages and bags were assumed to be using bags alone, and the single lease using cages, bags, and glued methods was also translated into bags. The single lease utilizing tables was also treated as bags, since the dimensions of these tables are unknown. The net effect of these decisions was to produce a high-end estimate of effective shading in these leases, which represent 11.66% of bag-equivalent culture occurring in the province. Following the above assumptions, the total gear coverage in NB sums to 16.4 ha, 1.89% of the active leased area in the province. Of this, 5.9 ha occurred in sites utilizing bags, with the remaining 10.5 ha in sites utilizing cages.

Detailed depth data from five bays (Bouctouche, Cocagne, Richibucto, Saint-Simon North, Tabusintac) were used to determine overlap with potential eelgrass habitat. These five bays represent 90.3% of all bag-equivalent culture in NB. Complete depth data were available for all leases in Cocagne and Tabusintac; for the other sites, the proportion of overlap was estimated only from leases with depth information, then extrapolated to the remainder of the leases in each bay. In Cocagne, the majority of leases and gear occurred in water < 3 m depth; in terms of gear coverage area, 3.2 out of 3.23 ha (99%) occurred over potential eelgrass habitat. A similar pattern was detected in Tabusintac with 3.4 out of 3.5 ha (97.1%) of gear area occurring over potential eelgrass habitat. Analysis of subsets of leases with depth data for the remaining bays found the proportion of gear coverage area within potential eelgrass habitat as 97.7% in Richibucto, 97.1% in Saint-Simon North, and 85.2% in Bouctouche.

For calculating overlap with potential eelgrass habitat in the remaining AMAs, the mean percent from the five bays with detailed depth information was used (95.2%). In sum, 15.5 ha of potential eelgrass habitat were estimated to be directly shaded by aquaculture gear.

Nova Scotia

Data representing aquaculture for sGSL Nova Scotia included publicly-available GIS layers from 2019 representing lease information as well as maximum gear estimates provided by the province that were derived from farm management plans developed for site applications. Gear quantities were provided in terms of 6-bag cages broken down by county. There was a discrepancy in the total leased area between 2019 lease data (349.3 ha) and information provided by the province (263.61 ha); this may be due to accounting for experimental or inactive leases, as well as changes occurring between 2019 and when this analysis was conducted in 2023. Both sets of numbers will be used to provide high and low estimates, with the mean value of 306.5 ha used for sGSL-scale estimation.

Information provided by the province for Pictou and Colchester counties combined accounted for 6 suspended culture leases (183.11 ha) with 43,920 gear units. This results in 5.93 ha of gear (3.2% of the leased area). Inverness County contained seven suspended leases (41.07 ha) with 6,532 gear units covering 0.882 ha (2.15% of the leased area). Antigonish County had four suspended leases (39.43 ha) with 6,110 gear units covering 0.825 ha (2.1% of the leased area). In sum, the estimated gear coverage from this dataset covers 7.64 ha (2.9% of the leased area). Extrapolating to the lease numbers from the 2019 dataset, assuming that all suspended leases with oyster listed as a farmed species (349.3 ha) contain 6-bag cages and average percentage of gear cover is 2.9% (based on NS-provided dataset above), gear coverage regardless of depth was calculated as 10.13 ha. Accordingly, the range of gear coverage in NS varied from 7.64 to 10.13 ha (mean 8.89 ha).

Detailed depth data from Merigomish (Pictou County) were used to determine the proportion of leases falling in potential eelgrass habitat. Approximately 29.2% of suspended leases in Merigomish fell within the < 3 m zone defined as potential eelgrass habitat. Assuming similar depth distribution for all Nova Scotia sGSL suspended leases, the area of potential eelgrass habitat covered by suspended leases ranges from 77.2 to 102.3 ha for the provincially-provided and 2019 datasets respectively. Applying the mean gear cover per hectare (2.9%) results in direct shading of potential eelgrass habitat ranging from 2.2 to 3.0 ha (mean 2.6 ha) for all sGSL suspended leases occurring in NS.

Implications for shellfish culture

Note that for the values presented below, numbers for NS represent the mean of the range of estimates. In sum, the total suspended oyster gear coverage across all three provinces, regardless of depth, was estimated at 93.7 ha (PEI: 68.4 ha; NB: 16.4 ha; NS: 8.89 ha; Table 6). Leased area (including only active leases in NB) for suspended oyster culture in all three provinces was 3,238.5 hectares (PEI: 2065.2 ha; NB: 866.8 ha; NS: 306.5 ha). Across the sGSL, suspended oyster gear covered 2.89% of these leases (PEI: 3.31%; NB: 1.89%; NS: 2.9%).

Accounting for depth, potential eelgrass shading was estimated at 19.13 ha (PEI: 1.03 ha; NB: 15.5 ha; NS: 2.6 ha). While the actual quantity and distribution of eelgrass throughout the sGSL is not known, this undoubtedly represents a vanishingly small proportion of existing habitat. For comparison, a recent satellite mapping exercise in Tracadie, NB measured 1259.9 ha of eelgrass (see Figure 5 below; DFO unpublished data); the estimated 19.13 ha of shading represents only 1.5% of the eelgrass habitat occurring in this single bay. Extrapolated over the dozens of aquaculture systems in the sGSL, this shading conservatively affects less than 0.1% of eelgrass habitat present in the region. In this context, the risk of suspended gear shading on eelgrass habitat at the regional scale is expected to be low, and other stressors (e.g., DFO 2012, those discussed above) are likely to be greater threats to the distribution and health of eelgrass habitat in the sGSL.

*Table 6. Summary of estimates representing potential shading of eelgrass habitat by suspended oyster culture in the three provinces of the sGSL. * Values for Nova Scotia represent the mean of the range of estimates. ** Leased area for New Brunswick only includes active leases identified in the source dataset.*

Province	Area shaded by suspended oyster culture, not accounting for depth (ha)	Leased area for suspended oyster culture (ha)	Percent of lease area shaded	Area of potential shading, accounting for depth (ha)
Prince Edward Island	68.4	2065.2	3.31%	1.03
New Brunswick	16.4	866.8**	1.89%	15.5
Nova Scotia*	8.89	306.5	2.9%	2.6
Total	***93.7***	***3238.5***	**-**	***19.13***

As supported by the light experiments and spatial analysis of potential gear shading presented above, oyster cage culture tends to result in reduced shading relative to suspended bag culture. The ongoing shift from suspended bag to cage culture has likely reduced shading of eelgrass, with suspended bags representing a worst-case scenario of shading (i.e., Skinner et al. 2014) compared to cage culture in deeper waters (i.e., the present study). While cages can still significantly shade eelgrass, particularly in depths of less than 2 m, our data suggest that cage culture situated in waters deeper than 2.5 m (allowing space above the seafloor for the eelgrass canopy) should not result in significant shading. As the spatial overlap analysis detailed, eelgrass habitat in aquaculture bays rarely occurs deeper than 3 m, suggesting the existence of shading “risk zones”: highest risk in shallow waters, moderate to low risk from 2–3 m, and very low to nonexistent risk at depths > 3 m (Figure 4). These findings represent a refinement of our understanding of the potential impacts of shading by aquaculture gear on eelgrass habitat under current practices in the sGSL. Management of aquaculture-eelgrass interactions thus should take into account gear type, water depth, and local context when assessing shading effects caused by suspended aquaculture gear. However, other considerations are also important; see the “knowledge gaps” section below.

Notably, changes in gear usage or culture practices (i.e., change in method/species, gear type, number and size of leases) can influence the shading footprint. Culture practices are dynamic, and changes are constantly occurring, so this analysis may need to be updated to reflect shifts in shellfish aquaculture practices in the sGSL. In particular, the depth distribution of PEI shellfish aquaculture trends deeper than in the other provinces likely because many leases began culturing mussels before changing to oysters. This distribution could shift shallower as the industry continues to prioritize oyster culture, potentially increasing eelgrass shading.

In NB, a large number of leases approved for suspended culture are currently inactive; 126 leases totaling 858.4 ha, or approximately double the area currently used for suspended oyster culture in the province. This represents a large pool of “latent effort” that could result in increased shading if these leases become active. NB also had the lowest proportion of gear coverage area of the three provinces at 1.89%. The reason for this is uncertain; however, it may be due to the high data quality provided by the Province, which was comprehensive and based on direct gear counts, whereas the datasets from the other provinces required estimation from site development plans and/or extrapolation from a subset of leases, and therefore could represent potential rather than realized gear usage. It may also be a function of the physical characteristics of NB culture areas, which are on average shallower than PEI and NS, and may include leased areas unsuitable for increased density of suspended culture. Nonetheless, any potential increase of NB gear coverage could also increase the shading footprint on eelgrass habitat.

In addition to changes to existing culture areas, the establishment of new suspended leases could also lead to increase eelgrass shading. For example, NS currently is reviewing multiple lease applications that could potentially increase the leased area in sGSL significantly; two suspended leases in Antigonish Harbour (total of 33.59 ha) are currently under review by the Nova Scotia Aquaculture Review Board, which would represent an increase of approximately 10% over current suspended oyster lease area for sGSL NS.

The sum of potential eelgrass habitat shaded by suspended oyster gear presented here is likely an overestimate, as it does not account for actual habitat suitability (aside from depth) or currently existing eelgrass. In reality, some of this shaded area will not be suitable for eelgrass, and some shaded areas likely contain eelgrass that is able to receive enough light for survival (particularly in waters deeper than 2 m). Similarly, the relatively low proportion of gear coverage in NB could be an indication that shading in NS and PEI could be overestimated, as proposed culture density seems to rarely be realized. Integration of high-quality data representing eelgrass distribution and aquaculture practices (including gear type and quantity) is critical for a more robust assessment of the impact of shellfish aquaculture shading on eelgrass habitat in the sGSL.

Conclusions

- In the sGSL direct shading by suspended aquaculture gear is most prevalent for oyster culture due to overlap with depth range for eelgrass habitat. Suspended mussel culture only overlaps potential eelgrass habitat in exceptional cases.
- Based on available data and current practices focusing on oyster cage culture, direct shading from aquaculture gear could affect an estimated total of 19.13 hectares of potential

eelgrass habitat in the sGSL which represents less than 0.1% of eelgrass habitat in the sGSL.

- The risk of shading from suspended oyster aquaculture on eelgrass habitat at the regional scale is expected to be low and context-dependent (Figure 4). Shading from aquaculture in the sGSL is unlikely to drive large-scale reductions in eelgrass coverage.

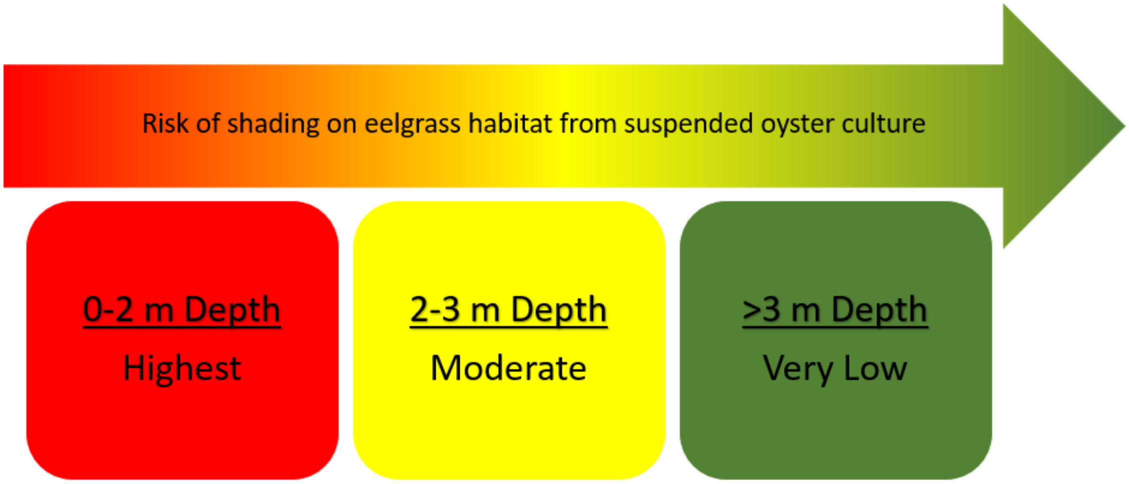

Figure 4. Depiction of the gradient of estimated “risk zones” for the shading of eelgrass habitat by suspended oyster aquaculture, as determined by water depth.

- The biological response of eelgrass to shading from aquaculture gear is complex, and further study would be needed to determine specific effects on eelgrass productivity and persistence at local and landscape scales. Other stressors are likely to be greater threats to the distribution and health of eelgrass habitat in the sGSL.
- Data representing actual eelgrass distribution and dynamics are critical for determining *actual* rather than *potential* interactions between suspended shellfish gear and eelgrass habitat.
- Multiple factors can directly affect the impact of shading by aquaculture gear on eelgrass habitat, including changes in eelgrass distribution, culture methods, or changes in the number of active sites. This Science Response represents current conditions, including the identification of important knowledge gaps.

Knowledge gaps

As described in detail above, a number of assumptions are required to estimate the potential scale of shading on eelgrass habitat in the sGSL. A large knowledge gap exists related to the spatial distribution of eelgrass itself. The spatial data presented for this Science Response only provides information regarding aquaculture leases. As such, we could only infer *potential* spatial overlap between aquaculture and hypothesized potential eelgrass habitat in the sGSL. A more detailed understanding would require knowledge of actual eelgrass distribution in the sGSL. While baseline information exists for certain areas of the sGSL, it is insufficient for accurately depicting the distribution of eelgrass across the region. Further, eelgrass habitat is highly dynamic with constantly shifting baselines over nested timescales, and multi-year data are necessary for understanding natural variability and naturally occurring extreme changes in distribution (Barrell and Grant 2015; Orth et al. 2022). Preliminary satellite imagery suggests that eelgrass distribution can vary substantially from year to year, complicating the establishment of proper baselines for monitoring and making management decisions (Figure 5).

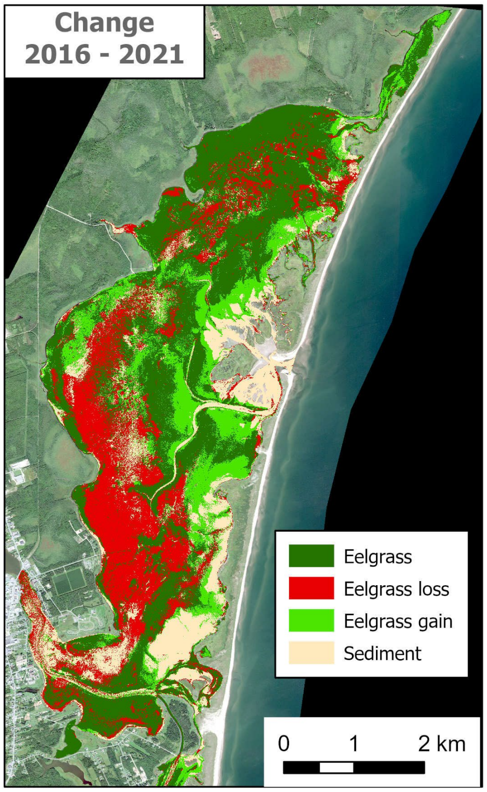

Figure 5. Dynamic change in eelgrass coverage from 2016 to 2021 as determined through analysis of high-resolution satellite imagery in Tracadie Bay, NB. The result of change over this period was the net loss of 164.4 hectares of eelgrass. The total vegetated area as of the 2021 image was 1259.9 hectares Source: DFO-Gulf, unpublished data.

It is also known that eelgrass does exist within aquaculture leases while it is absent from adjacent areas with no aquaculture, further complicating the issue. This suggests the likelihood of shading causing stress short of mortality in many cases, which suggests the need for interpretation through a cumulative effects framework. As such, a full understanding of aquaculture effects on eelgrass requires a quantification of eelgrass distribution with respect to intra- and interannual variation. Eelgrass dynamics may differ between bays, requiring different approaches to management depending on local context. Efforts by DFO Science and MPC sectors are currently pursuing mapping eelgrass habitat throughout the sGSL with satellite imagery, however the data were not available for this process (Monica Boudreau, DFO-MPC, pers. comm.).

Aside from the knowledge gaps regarding the actual distribution and natural variability of eelgrass, direct links between aquaculture activities and eelgrass productivity at ecosystem-scale are relatively unexplored in the sGSL. The current process examined the spatial scale of potential shading effects, but did not evaluate the response of eelgrass to shading from suspended aquaculture gear. Though previous studies have provided insights at the local scale (e.g., Skinner et al. 2013, 2014), these efforts only investigated the suspended bag culture method, which this process has demonstrated is increasingly uncommon in the sGSL, and in very shallow depths not representative of current practices. While the light experiment conducted for this process increases knowledge about shading effects related to additional types of suspended gear, direct links with eelgrass productivity and distribution could not be established with available data. Understanding links to eelgrass productivity and realized net effects of shellfish culture on eelgrass habitat requires further study across the diverse contexts under which shellfish culture occurs in the sGSL.

Interpretation of the significance of the potential shading described above is difficult in absence of data representing the status of eelgrass habitat outside of leased areas. While the total area of directly shaded potential eelgrass habitat can be reasonably interpreted as a small proportion of extant eelgrass, it is important to interpret these results within the context of the eelgrass landscape in aquaculture bays. Eelgrass can occur in various spatial distributions, with direct implications for biological processes and the provision of ecosystem services (Barrell et al. 2015). For example, local shading could be presumed to have increased significance in bays with very little eelgrass cover, or that have already experienced documented declines, highlighting the need for understanding the local landscape dynamics of eelgrass habitat to help guide management decisions.

The data presented herein regarding the spatial footprint of aquaculture in the sGSL vary in terms of resolution between provinces, gear types, and farmed species; other parameters that could also influence shading (e.g., culture density, biofouling, boat traffic at culture sites, etc.) are also unknown from the available data. Standardizing the way in which these data are reported for different provinces, gear types, and cultured species, as well as enhancing the degree of information available (e.g., adding stocking densities, boat traffic, etc.) would help in resolving this issue of data resolution.

It is also important to reiterate that this Science Response only deals with direct effects of shading, but other pathways of aquaculture can impact eelgrass. There is no information within the sGSL on the net effects of aquaculture (i.e., filtration and deposition, physical disturbance, and shading) related to eelgrass (Howarth et al. 2022). The positive pathways of interaction through reducing turbidity, reducing epiphyte propagule loads, and fertilization have not been locally demonstrated (Newell and Koch 2004; Sandoval-Gil et al. 2016; Smith et al. 2018). Preliminary model results suggest that the filtration activities of cultured bivalves can improve light availability for eelgrass, however the magnitude of improvement, which can reach over 8% bottom light increase in non-shaded farm areas, was only estimated in one bay and resultant effects on eelgrass productivity metrics have not been assessed (Ouellette et al. 2014, PARR-2014-G-10). Moreover, the contribution of organic matter in local beds is unknown from oysters outside select operations (e.g., Skinner et al,. 2013), which negatively affects eelgrass growth and density (Wicks et al. 2009; Borum et al. 2014). These complications related to net effects are further compounded by the fact that certain pathways can affect different eelgrass life history traits and are context-dependent (Robertson and Mann 1984; Garbary et al. 2014; Skinner et al. 2014; Castorani et al. 2015; McIver et al. 2019; van den Heuvel et al. 2019; Howarth et al. 2022). It is thus critical to recognize that quantifying the overall impact of aquaculture on eelgrass is very complicated and requires detailed assessments of how multiple impact pathways affect multiple biological traits across multiple spatial and temporal scales.

On top of net effects from aquaculture, it is also crucial to consider cumulative effects from multiple stressors on eelgrass (Murphy et al. 2019; Orth et al. 2022). In the sGSL, temperatures can often exceed the documented threshold for eelgrass survival (Nejrup & Pedersen 2008; Sonier et al. 2011). Such effects will almost certainly be compounded as the climate continues to warm. Climate change is also driving shifts in other environmental factors that can influence eelgrass distribution in the sGSL, such as the frequency and severity of storm events and nearshore ice dynamics in winter (Schneider and Mann 1991; Murphy et al. 2021). Increased storm severity can result in eelgrass damage or destruction (Wicks et al. 2009; Murphy et al. 2021) while reduced ice cover in winter can increase eelgrass coverage (Warren et al. 2010), though lack of winter ice may cause increased vulnerability to winter storms. Furthermore, increases in land use intensity within local watersheds can introduce light-capturing materials (i.e., humic-organics and/or inorganic particulates) or nutrients which induce the growth of algae in eutrophic systems, which may affect aquaculture-eelgrass interactions (Wong et al. 2013; van den Heuvel et al. 2019; Orth et al. 2022).

It is also important to recognize that changes to aquaculture practices are ongoing. Harvesting methods, gear types, and decisions regarding the spatial placement of aquaculture leases (among other aspects of the industry) are constantly evolving (Medcof 1961). Many of these management and logistical changes are put in place to reduce impacts on eelgrass and other important species/habitats. The impacts of aquaculture on eelgrass highlighted in this SRR thus may not exist under future culture practices in the sGSL. As such, aquaculture-eelgrass interactions will require re-evaluation in the future.

This Science Response has focused on *Z.marina* interactions with shellfish aquaculture; however, in coastal zones which regularly experience < 10 PSU salinity, *Ruppia maritima* (Widgeon grass or Sea ditchgrass) naturally replaces eelgrass (Lefcheck et al. 2018; van den Heuvel et al. 2019). Widgeon grass, though mostly a brackish species, is often grouped with seagrasses in ecological assessments, provides similar ecosystem services as eelgrass, and is faced with similar external pressures (Newell and Koch 2004; Moore et al. 2014; Orth et al. 2022). Likewise, there are cases where Widgeon grass grows in areas formerly occupied by eelgrass (Moore et al. 2014; DFO-Gulf unpublished data). Moreover, oysters may provide similar positive benefits to *R. maritima* biomass (Newell and Koch 2004), but coverage for this species may also change from physical disturbances such as boat propeller scarring (Orth et al. 2017). Some oyster growers temporarily place their product in freshwater areas to kill off biofouling species (Méthé et al. 2015), which may result in some limited effects of oyster aquaculture on widgeon grass in low salinity areas. However, it is believed that only a small fraction of oyster growers use this method to reduce biofouling, and an increasing shift to oyster cage culture (which removes biofouling organisms via air exposure) further reduces aquaculture-widgeon grass interactions. Nevertheless, there exists a data gap in the distribution and basic life-history knowledge of widgeon grass in the sGSL and the impacts of aquaculture on this ecologically important species—while likely negligible—remain unstudied. Widgeon grass is known to occur in coastal zones throughout the sGSL (DFO unpublished data), though it is relatively understudied compared to eelgrass.

Finally, while this Science Response focused on the direct impacts of aquaculture shading on eelgrass habitat, impacts on the range of ecosystem services that eelgrass provides must also be recognized (Hansen and Reidenbach 2013; Ferriss et al. 2019; Orth et al. 2020). Notably, eelgrass beds in the sGSL provide structural habitat for many fish and invertebrate assemblages (Joseph et al. 2006; Coffin et al. 2018). However, there is a lack of information on how local fish interact with eelgrass landscape characteristics in this region (e.g., bed size, patchiness, length of meadow edge, etc.), and it is unknown if changes in eelgrass traits translate into concurrent changes in species-specific populations in the sGSL of fish and other taxa that utilize eelgrass (Thistle et al. 2010; Jiménez-Ramos et al. 2019). As such, the downstream consequences of aquaculture-eelgrass interactions on populations of other species and the biological communities of eelgrass beds in the sGSL warrant research attention.

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Appendices

Appendix I: Depictions of suspended oyster bag and cage aquaculture

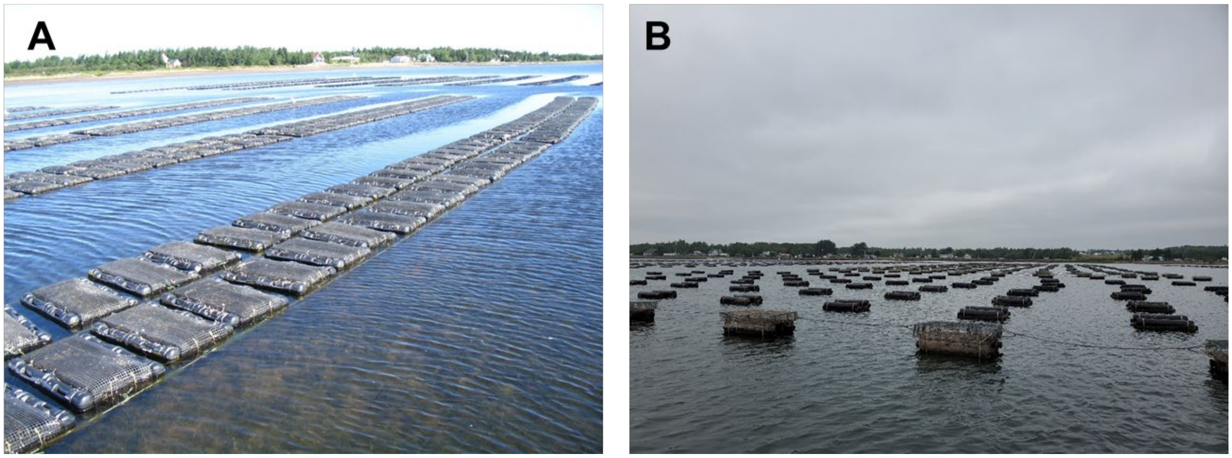

*Figure A1.1. Visual comparison of a typical oyster bag lease (**A**) versus a typical oyster cage lease (**B**). Note that the first row of cages in **B** are "flipped up" for removing biofouling, while the remaining cages are submerged for oyster growth. Photo credits: S. Doiron **(A)**, J. Barrell **(B)**.*

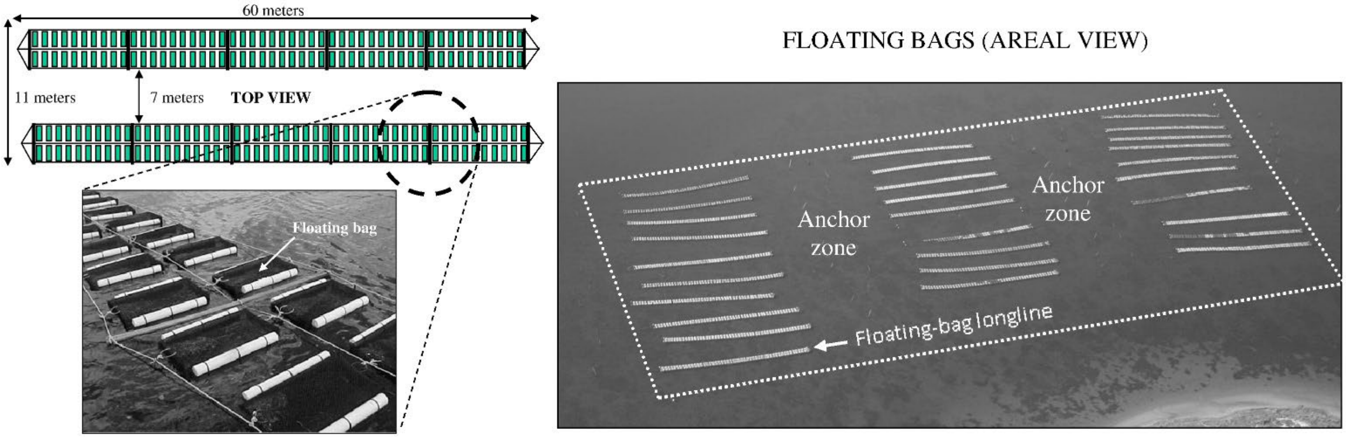

Figure A1.2. (left) Depiction of suspended bag oyster aquaculture as commonly practiced in the sGSL. Individual floating bags are attached in pairs to a central longline anchored at both ends. (right) Aerial view of a lease with multiple longlines. From Comeau (2013).

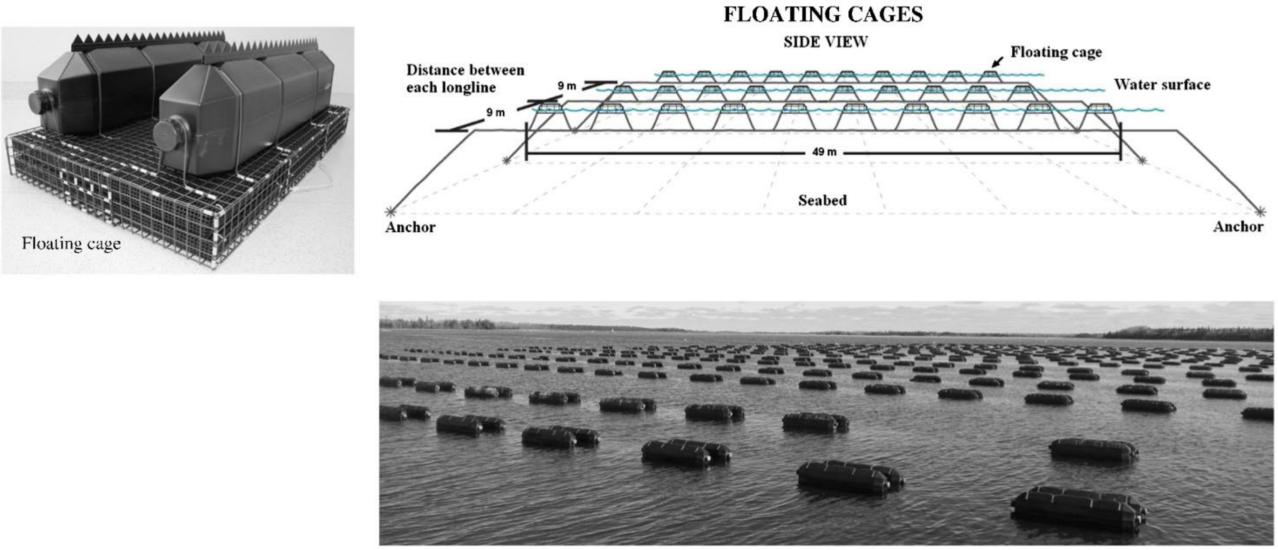

Figure A1.3. (above) Depiction of suspended oyster cage culture as commonly practiced in the sGSL. Individual cages are attached along an anchored longline system with space left between culture units. (below) Multiple longlines distributed throughout a lease. From Comeau (2013).

Appendix II: Detailed methods for light experiments

Study region

Cocagne Bay is a typical southern Gulf of St. Lawrence semi-enclosed embayment with a mean depth of 1.7 m and relatively low tidal range of approximately 1 m (Figure A2.1).

Over the course of a few weeks in late summer 2021, two field experiments were conducted to characterize the underwater light field in the vicinity of a suspended oyster farm using the OysterGro^{TM} technique.

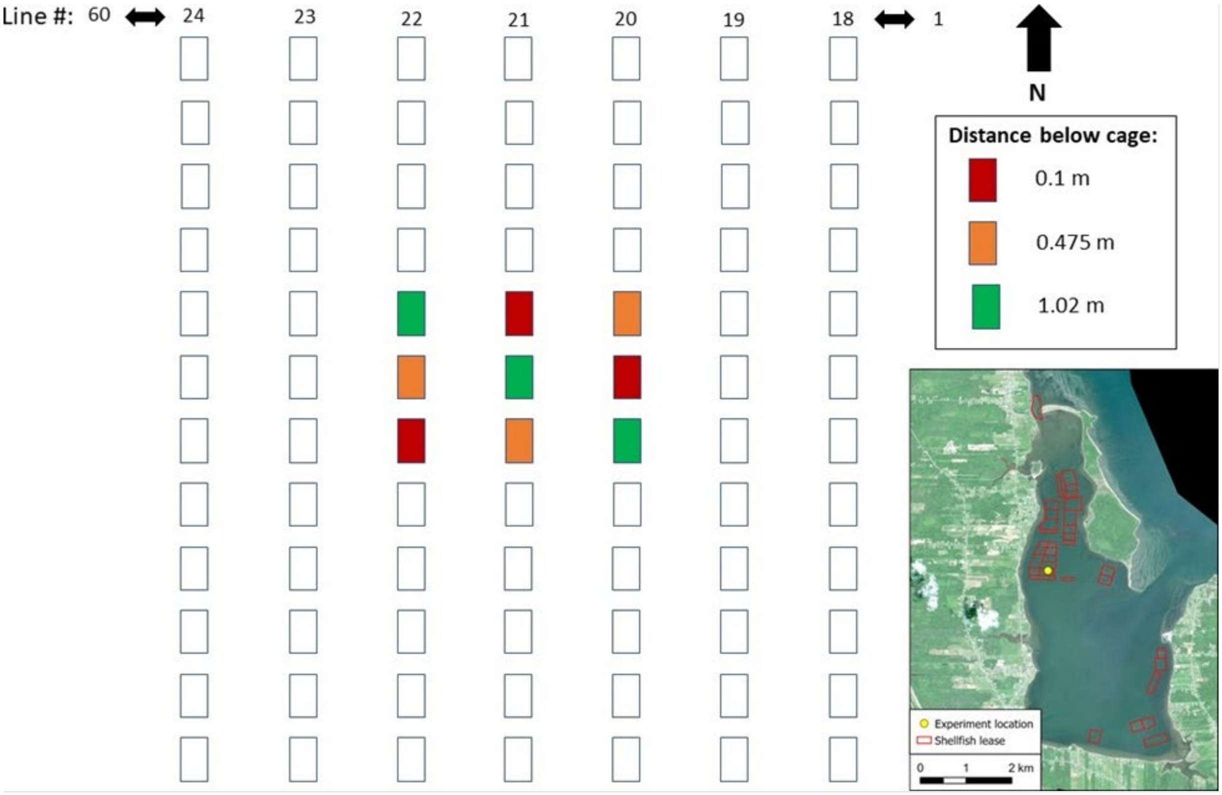

Figure A2.1. Location of the experimental site in Cocagne Bay, NB (both experiments) and distribution of the depth treatments of experiment #2 among the cages of the selected lines within the study farm.

Experiment #1

This first experiment aimed at evaluating suspended oyster farm-scale effects on bottom light levels and light attenuation. Photosynthetically Active Radiation (PAR) sensors (Odyssey submersible PAR sensor, Dataflow Systems Ltd, New Zealand) were deployed on the bottom of Cocagne Bay, NB, both under an oyster cage farm and at a control station outside the farm (approximately 100 m to the north). Duplicate sensors were deployed at each location on vertical rods mounted on flat steel tripods lying on the sea bed and holding the sensors in a vertical position at 0.735 m off-bottom.

At the farm location, the duplicate sensors were deployed at 6 sites distributed on a North-South/East-West grid such that, initially, one pair of sites was directly under an oyster cage line, another pair was directly under the adjacent oyster cage line and the last pair of sites was directly in between these two cage lines. Oyster cage lines are only anchored at each extremity, which provides some freedom of movement to each cage along the line. Cage movements were not monitored during the experiment but the grid arrangement of sensors was meant to provide a representative estimate of light conditions at the farm-scale. All seven (six within farm and one control outside) bottom deployment platforms were also equipped with pressure sensors (HOBO U-20, Onset) to measure water depth and its variations through time during the entire experiment.

At the control station an additional PAR sensor was deployed on a weighed PVC frame equipped with buoys to hold the sensor in a vertical position and at a constant depth (Z_S = 0.1 m) to measure surface light intensity. This experiment covered a period of 7 days from

10 August to 17 August 2021 and all light and pressure sensors were set to record every 5 min. All light sensors were simultaneously calibrated prior to deployment, against measurements from a LI-193 PAR sensor (LI-COR Biosciences, Nebraska, USA) to provide light intensity values in µmol photons m^{-2} s^{-1}. One of the sensors deployed under the oyster farm did not record any data, bringing the total number of farm measurement locations to 11 (Table A2.1).

Simultaneous bottom (I_C) and surface (I_S) light intensity values at the control site were used to estimate a light extinction coefficient (K_D in m^{-1}), assuming the bulk PAR attenuation through the water column followed the Beer-Lambert law:

$$K_D = -\frac{1}{(Z_C - Z_S)} ln\left(\frac{I_C}{I_S}\right) \qquad \text{Eq. 1}$$

Where Z_C is the depth of the bottom control sensors provided by the corresponding pressure sensor.

All bottom farm sensor measurements (I_{Fn} for n = 1 to 11) were then corrected for the slight differences in deployment depth (summarized in Table A2.1) using the control site depth (Z_C) as a common reference, the depth provided by pressure sensor data from the respective deployment platforms (Z_{Fn*} for $n*$ = 1 to 6, only one pressure sensor per platform) and the light extinction coefficient calculated above:

$$I_{Fn}(Z_C) = I_{Fn}(Z_{Fn*})e^{-K_D(Z_C - Z_{Fn*})} \qquad \text{Eq. 2}$$

Light conditions within the farm could then be compared to the control outside, both in terms of integrated light intensity at the bottom for the whole experiment period and light extinction coefficient calculated at each farm site using Eq. 1 and replacing the control intensity (I_C) by intensity at each site (I_{Fn}).

Table A2.1. Locations and summary data for Experiment #1 light and pressure sensor deployments in Cocagne Bay (mean ± SE).

Site	Latitude	Longitude	Mean Light Sensor Depth (Z_X, m)	Mean Integrated Light Intensity (I_T, mol photons m^{-2} d^{-1})	Daily Integrated Light Intensity (% of sub-surface)	Mean Light Extinction Coefficient (K_D, m^{-1})
Control Surface	46.3689	-64.6070	0.100	28.71 ± 2.29	-	-
Control Bottom	46.3691	-64.6070	2.147	9.28 ± 0.68	32.49 ± 0.67	0.592 ± 0.0002
Farm1	46.3679	-64.6071	2.149	8.65 ± 0.47	30.30 ± 0.71	0.677 ± 0.0044
Farm2	46.3680	-64.6071	2.102	8.49 ± 0.42	29.77 ± 0.66	0.642 ± 0.0007
Farm3	46.3681	-64.6071	2.085	8.21 ± 0.63	28.73 ± 0.88	0.653 ± 0.0022

Site	Latitude	Longitude	Mean Light Sensor Depth (Z_X, m)	Mean Integrated Light Intensity (I_T, mol photons m^{-2} d^{-1})	Daily Integrated Light Intensity (% of sub-surface)	Mean Light Extinction Coefficient (K_D, m^{-1})
Farm4	46.3680	-64.6070	2.108	7.74 ± 0.53	26.88 ± 0.90	0.704 ± 0.0007
Farm5	46.3682	-64.6071	2.097	8.79 ± 0.50	30.64 ± 0.54	0.628 ± 0.0001
Farm6	46.3680	-64.6070	2.085	8.08 ± 0.53	28.21 ± 1.02	0.667 ± 0.0005

Experiment #2

This second experiment was designed to test the direct light attenuation under oyster cages at different depths. The same Odyssey PAR sensors were deployed on PVC frames hanging from oyster cages at different distances below the cages. Deployment frames were cross-shaped with arms matching the cage dimensions and meeting in the center of the cage where one PAR sensor was attached. Each frame was weighed in its center with a 5 kg piece of chain to restrain movements of the frame as much as possible under the cage and hold the sensor in a vertical position.

Oyster cages used in the study farm were 20 cm thick and were held 5 cm below the water surface by two buoys on top. Hence, the bottom of the cages, where the deployment frames were suspended, was located 0.25 m below the surface. Two pieces of rope going through the arms of each deployment frame were used to suspend the frame from the center points of the four edges of the cage and adjusted in length to hold the PAR sensors at 0.1, 0.475 and 1.02 m below the cage or 0.35, 0.725 and 1.27 m below the water surface. Each depth treatment was repeated three times under cages of three adjacent lines located in the center part of the farm (Figure A2.1, lines #20, 21 and 22 from the eastern edge of the farm). Depth treatments were distributed randomly among the 3 cages of each selected line. Lines in the study farm were roughly aligned along the North-South direction.

The same Control station as in Experiment #1 was equipped again with a sub-surface PAR sensor, two bottom PAR sensors and a pressure sensor to record water depth variations throughout the experiment. All PAR sensors were calibrated prior to deployment as in Experiment #1. The experiment lasted over a full 24-hr cycle in late September 2021 and sensors were set to record every 5 min. Figure A2.2 provides an example of raw data from the PAR sensors both within (Line #21) and outside the farm. Besides the expected stronger attenuation closer to the cages, these data show that any location deeper than 0.1 m below the farm receives direct shading from a cage only during part of the day (see change in light intensity temporal pattern indicated by the arrows).

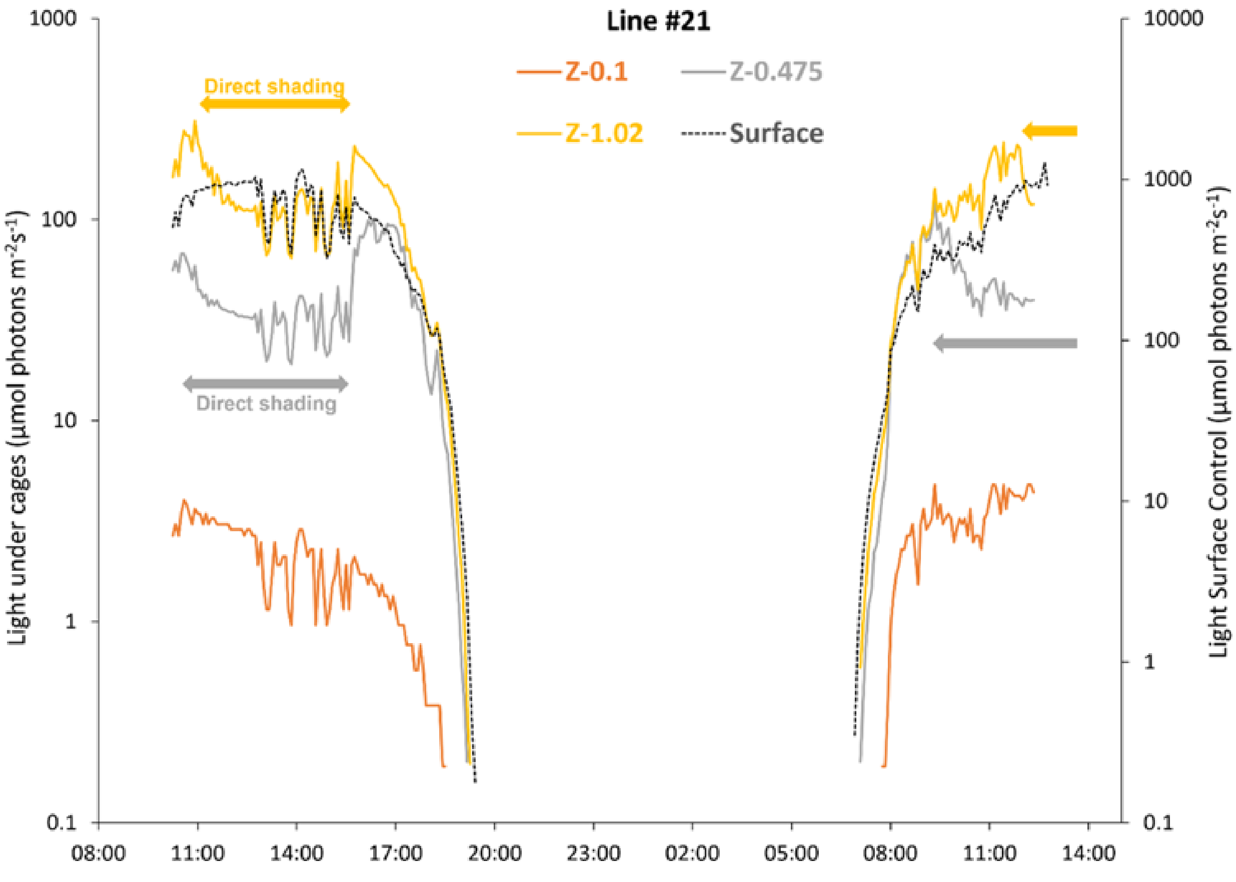

Figure A2.2. Time series of light intensity at the three different depths tested (z = 0.1, 0.475 and 1.02 m) under oyster cages of Line #21 (left axis) and at the sub-surface control station (right axis). Intensity values are plotted on a logarithmic scale to help comparison of series from different depths.

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