Marine Pollution Bulletin 127 (2018) 297–309

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Influence of salmonid aquaculture activities on a rock-cliff epifaunal community in Jervis Inlet, British Columbia

T.F. Sutherland*, A.M. Sterling, M. Ou

Fisheries and Oceans Canada, 4160 Marine Drive, West Vancouver, B.C. V7V 1N6, Canada

ARTICLE INFO

Keywords:
Aquaculture
Video
Rock
Sponge
Bacteria
Carbon-flux

ABSTRACT

Benthic video surveys were carried out at two marine finfish aquaculture and associated reference sites in Jervis Inlet (JI), British Columbia. Substrate composition, epifaunal diversity, mat-forming taxa (primary indicators: opportunistic polychaete complexes (OPCs) and sulfide-oxidizing bacteria) and waste pellets were quantitatively assessed. Hard-bottom substrates were dominated by rock wall, skeletal sponge matrix, graded bedrock, rock-veneer, and cobble. Aquaculture waste outputs (modelled depositional carbon fluxes and observations of waste feed/faecal pellets) were correlated with benthic organic enrichment indicators (OPC and sulfide-oxidizing bacteria). Sulfide-oxidizing bacteria varied in abundance up to a modelled depositional carbon flux of ~2 gC m^{-2} day^{-1} where it sustained 50% areal coverage. Glass sponges revealed an inverse relationship with aquaculture waste outputs and sulfide-oxidizing bacteria. Plumose anemones and shrimp showed a low frequency of occurrence at reference sites; however, they were abundant within the near-field zone of the aquaculture sites associated with a higher modelled carbon flux. Future research should focus on the response of various taxa to depositional gradients and their potential role as secondary indicators of aquaculture activities associated with rock-cliff communities.

1. Introduction

Aquaculture environmental monitoring and research programs designed to assess benthic organic enrichment gradients typically employ conventional sediment grab or core mechanisms (e.g., Van Veen, Petite Ponar, Smith-McIntyre; Somerfield et al., 2005) conducive to the collection of chemical and biodiversity indicators from soft substrates (AAR, 2015). Abiotic chemical indicators of benthic organic enrichment may include sediment porewater sulfide concentration, sediment organic content, and trace-element concentration (Wildish et al., 2001; Brooks and Mahnken, 2003; Brooks et al., 2003; Sutherland et al., 2001, 2007a, 2007b), while biodiversity indicators may include both 1) infauna, consisting of meiofauna (0.063 mm–0.5 mm) and macrofauna (> 0.5 mm), and 2) epifauna, consisting of mat-forming microbes (sulfide-oxidizing bacteria) and opportunistic polychaete complexes (OPCs) (Weston, 1990; Sutherland et al., 2007b; Emmett et al., 2007; Hargrave et al., 2008; Hamoutene, 2014; Ross et al., 2016). Biological responses of infauna and epifauna to abiotic indicators (e.g. dissolved sulfide) can be used to develop management thresholds (Sutherland et al., 2007b; Hargrave et al., 2008; AAR, 2015). However, the successful collection of sediment porewater sulfide from soft- or mixed-substrates relies on sufficient silt-clay (< 63 μm) and organic content to create conditions conducive to microbially-mediated sulfate reduction and accumulation of dissolved sulfide in sediment porewaters. A cohesive sediment fabric is further required to facilitate preservation of porewater sulfide signatures during grab-sample ascent and handling on boat decks.

Although some studies have examined epifaunal indicators representing organic enrichment in relation to porewater sulfide concentrations on mixed-bottom seafloors (Hamoutene, 2014), few studies have examined epifaunal responses to aquaculture activities on true hard-bottom environments that are absent of a sulfide-laden sediment fabric. True hard-bottom substrates ("non-grabbable") cannot be sampled with traditional coring and grab methods, and are dominated by bedrock and/or mixed-bottom substrates where the latter is typically characterized by low silt-clay content, low level of cohesion, and compact and/or loose large-grained sediments. These substrates are not conducive to sulfate reduction and the associated accumulation of porewater sulfide. Thus, knowledge gaps exist regarding the development of regulatory thresholds for epifauna responses to organic enrichment on solid bedrock and mixed-bottom substrate environments where traditional chemical indicators cannot be collected.

While visual-monitoring can be used to identify epifauna on soft-, mixed- and hard-substrates (Crawford et al., 2001; Emmett et al.,

---

* Corresponding author.
E-mail address: Terri.Sutherland@dfo-mpo.gc.ca (T.F. Sutherland).

https://doi.org/10.1016/j.marpolbul.2017.12.005
Received 8 March 2017; Received in revised form 19 November 2017; Accepted 2 December 2017

2007), it represents an essential tool for the examination of hard-bed-rock substrates dominated by vertically-structured or mat-forming epifauna that cannot be detached from rock surfaces in a quantitative manner using grab mechanisms. In B.C., bedrock epifauna are mainly found on the steeply-sloped walls of fjords, archipelago channels, and sounds, as well as basin seafloor outcrops (Levings et al., 1983; Tunnicliffe and Wilson, 1988; Leys et al., 2004; Yahel et al., 2007; Cook et al., 2008; Sutherland et al., 2016). Bedrock epifauna observed through video surveys on the west coast of Vancouver Island (fjords & inlets), Queen Charlotte Strait, Johnston Strait, and Strait of Georgia (JI system), includes sponge communities, anemones, squat lobsters, giant sea cucumbers, cup corals, tube-dwelling worms, and urchins (Sutherland et al., 2016). Given the vast distance and complexity of the British Columbia (B.C.) coastline with regards to oceanographic and bathymetry features (Zacharias et al., 1998; DFO, 2009), it is important to further classify various true hard-bottom habitats according to hydrodynamic regimes, depth, slope, and ledges to identify the relationships between substrate attributes and epifaunal diversity. Rock-cliff habitats within deep fjords that harbour unique sponge communities (Farrow et al., 1983; Levings et al., 1983; Leys et al., 2004), for example, may serve as the end of a continuum within a true hard-bottom substrate spectrum for examining aquaculture-environmental interactions. While these sponge communities create a complex habitat structure for invertebrates (Cook et al., 2008; Sutherland et al., 2016), they may be vulnerable given their delicate structure, slow growth rates, and susceptibility to high sedimentation rates (DFO, 2010a, 2010b, 2013; Boutillier et al., 2013; Leys and Lauzon, 1998; Leys, 2013).

Largely due to logistical hindrances associated with the sampling of rocky steep habitats, there is currently a dearth of information relating to the environmental effects of finfish aquaculture on true hard bottom substrates. The objective of this study was to examine epifaunal distribution and abundance in relation to salmonid aquaculture operations located on a fjordic rock-cliff setting in Jervis Inlet (JI), B.C. The relationship between epifauna, established indicators of aquaculture-derived benthic organic enrichment (sulfide-oxidizing bacteria, OPC), modelled depositional carbon flux and substrate type were examined in the absence of a conventional porewater sulfide impact classification system compatible with soft- and mixed-bottom substrates. Emphasis was placed on certain taxa that are 1) sensitive to sedimentation and part of federal governmental conservation strategies (e.g. glass sponges; DFO, 2010a, 2010b; Boutillier et al., 2013; Leys, 2013) and 2) abundant and elicit strong preference or avoidance responses to aquaculture operations (potential indicator within steep rock-cliff settings). The high spatial-resolution of the contiguous 2-m video segments along the length of the ~300-m video surveys, as employed in this study (east and west surveys combined at each site), provides confidence in the distribution of substrate, biodiversity, and aquaculture waste indicators relative to that of discrete sampling that may provide a non-representative distribution of these variables. In addition, this high-resolution video sampling design allows for the identification of gradual or abrupt responses of potential taxa indicators within proximity of the aquaculture operations to support the study objectives.

1.1. Study site description

The aquaculture sites, Ahlstrom Point (AP) and Culloden Point (CP), are located inside the entrance of JI, B.C. (Fig. 1), which is located approximately 73 km northwest of Vancouver. JI is one of the deepest fjords in B.C. with a length of 89 km, a mean width of 3.1 km, and a basin depth range of 350 to 730 m (Pickard, 1961). JI is made up of 10 adjoining basins divided by a series of sills (Lazier, 1963; Pickard, 1961), with the study site located in the outer basin (Fig. 1). JI is considered a "deep-silled" fjord (sill depth of 385 m), where bi-directional flow across the sill entrance results from a net movement of surface water seaward and counter-current flow up-inlet below the surface layer (estuarine circulation). The adjoining "shallow-silled fjords" (Princess Louisa, Sechelt, and Narrows Inlets) have sill depths between 5 and 14 m that produce a turbulent jet and predominantly uni-directional tidal waters near the inlet mouth. Relatively low levels of stored snow reserves and low mean annual freshwater discharge (180 $m^3 * s^{-1}$) result in weak estuarine circulation and slow deep-water renewal in JI (Lazier, 1963; Pickard, 1961). Consequently, physical water properties do not vary appreciably below 300 m. A dissolved oxygen-minimum zone (< 2 mg L^{-1}) can develop at an intermediate water layer due to the following sequential events: 1) slow deep-water renewal or entrainment resulting from weak estuarine circulation (Lazier, 1963; Pickard, 1975; Timothy et al., 2003); 2) seasonal degradation (i.e., microbial respiration) of plankton blooms generated in the euphotic zone at head of JI; and 3) an outflow current down-inlet that counters either a significant intrusion of an oxygenated saline deep-water mass over the entrance sill and up to the inlet head and/or a significant meteorological events (wind) that dominate estuarine circulation down-inlet (Lazier, 1963; Pickard, 1961). Grill (1978) described a dissolved manganese (Mn) gradient extending down the length of JI within the intermediate outflow layer (150–300 m depth interval), that mirrored that of dissolved-oxygen, supporting the occurrence of suboxic redox processes. A frontal zone characterized by high primary productivity exists where the mouth of JI, Agamemnon Channel, and Skookumchuck Narrows intersect (Parsons et al., 1984). In general, the timing and composition of phytoplankton blooms rely on the degree of stratification which is influenced by freshwater runoff and wind conditions (Sancetta, 1989). The diatom-dominated spring bloom is closely followed by a mixed population of diatoms and flagellates; the latter typically restricted to low-nutrient and stratified summer conditions (Sancetta, 1989). The appearance of flagellates is likely influenced by 1) spillover across the shallow sills of stratified adjoining inlets (e.g. Sechelt Inlet) characterized by lower nitrogen (N):phosphate (P) ratios; and 2) nanoflagellate populations that sustain background population levels despite decreases in nutrient levels (Smethie, 1987; Sutherland, 1991; Haigh et al., 1992; Taylor et al., 1994).

Depositional fluxes of organic carbon and biogenic silica mirror annual primary production cycles, showing increases in the spring and decreases in the fall (Timothy et al., 2003). Deposited amorphous silica is mainly composed of diatom frustules with minor contributions from silicoflagellates (Sancetta, 1989; Sancetta and Calvert, 1988). Surface dissolved silica concentrations are lower than those below the thermocline (25 m), with deepwater concentrations > 50 μmol L^{-1} (Leys et al., 2004). Tidally-driven resuspension, particle focusing, or increasing trapping efficiency with depth, are continual sources of additional particle fluxes to the mid and deep water column (Timothy, 2004). Deepwater renewal events periodically contribute debris to bottom waters.

The glacier-carved vertical walls of JI are dominated by granodiorite, an intrusive plutonic igneous rock made up of exposed silica-rich magma, which cooled and formed subsurface batholiths (Tunnicliffe and Wilson, 1988; Levings et al., 1983). Granodiorite contains $> 20\%$ quartz by volume and a plagioclase feldspar composition of 65–95% that is mined historically by local quarries. The rocky cliff communities are represented by both sedentary invertebrates (anemones, tube-dwelling worms, cup coral, sponges, brachiopods) and mobile invertebrates (squat lobsters, asteroids, shrimp, polychaetes, and urchins) (Levings et al., 1983; Sutherland et al., 2016). High densities of reef-forming glass sponges (Dictyonine) exist above 200 m (sponge belt) with sharp reductions in abundance between 200 and 700 m. Relatively low densities of non-reef-forming sponges (lyssacine) occur along the rock-cliff profile (Leys et al., 2004).

2. Materials and methods

Benthic video surveys were carried out at aquaculture sites at AP (Label: JI-1; June 2009) and CP (Label: JI-2; April 2008) as shown in