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Passive reclamation of soft-sediment ecosystems on the North Coast of British Columbia, Canada

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ABSTRACT

Estuarine ecosystems are degraded through anthropogenic development, leading to reduced habitat suitability for biological communities. The Skeena River estuary (British Columbia, Canada) is undergoing passive reclamation from historical salmon canneries and pulp mills, while localized disturbances continue at present. To reveal both current impacts and the trajectory of passive reclamation from historical activities, the intertidal mudflat surrounding the longest operating salmon cannery, Cassiar Cannery, within the Skeena estuary was surveyed. Nutrient availability (chlorophyll *a* concentration/organic matter content), sediment variables (particle size, water content, penetrability, woody debris/macroalgae cover, apparent redox potential discontinuity depth), and infaunal community composition varied spatiotemporally, and suggest that an old dock may be influencing the infaunal community given the abundance of disturbance indicating taxa below the dock. However, with populations of amphipods, mobile polychaetes, and a complex community structure, the mudflat as a whole appears to be relatively healthy. Therefore, cessation of historic activities has allowed for passive reclamation to a reasonably unstressed state, though a threshold of recovery may exist for intertidal mudflats beyond which passive reclamation will not be effective.

1. Introduction

Soft-sediment ecosystems represent over 70% of coastal ecosystems, and are important components of estuarine habitats (Constable and Fairweather, 1999; Schlacher and Thompson, 2013). Estuaries are productive regions with importance for commercial fisheries, providing habitat for sensitive species (especially migratory shorebirds), as well as recreational uses for human populations (Carr-Harris et al., 2015; Constable and Fairweather, 1999; Dissanayake et al., 2018; Kennish, 2002). However, urbanization and industrial development have resulted in the degradation of soft-sediment ecosystems and estuaries (Constable and Fairweather, 1999; Crain et al., 2008; Kennish, 2002; Schlacher et al., 2016). Coastal developments will increase as human populations grow, with the associated habitat degradation leading to substantial ecological consequences (Dissanayake et al., 2018; Kritzer et al., 2016). As such, understanding human impacts and subsequent management is now a fundamental component of research into coastal and estuarine ecology (Gonzalez et al., 2016; Vackar et al., 2012).

Within estuarine soft-sediments, detrimental effects can occur through physical damage to the substrate surface, organic enrichment, oxygen depletion, and accumulation of contaminants (Dernie et al., 2003; Pearson and Rosenberg, 1978). Physical disturbance results in the creation of surface features such as pits and troughs, thus allowing water accumulation, disturbing biological communities and structures, and possibly disrupting the redox potential discontinuity (RPD; transition from oxidizing to reducing sediment conditions) layer (Dernie et al., 2003; Fonseca et al., 1982; Hansen and Skilleter, 1994). Organic enrichment, such as from human sewage or effluent from pulp mills, can substantially alter infaunal biodiversity and community composition (Ahn et al., 1995; Buttermore, 1977; Caswell et al. 2018; Heilskov and Holmer, 2001; Pearson and Rosenberg, 1978) and potentially lead to oxygen depletion and anoxia (Buttermore, 1977; Kristensen, 2000; Levin et al. 2009; Waldichuk, 1979). Such enrichment can also lead to sulphide accumulation, altering infaunal communities through toxicological effects and exacerbation of hypoxia (Heilskov and Holmer, 2001; Wu, 1995). Furthermore, sediment contamination is not restricted to organic enrichment and occurs through pollution and industrial effluents containing polycyclic aromatic hydrocarbons, sulfides, coppers and other chemicals (Hoos, 1975; Turner, 2019; Yunker et al., 2002), with negative impacts on infaunal communities (Pires et al., 2017; Pocklington and Wells, 1992; Waldichuk, 1966).

Due to their well-understood responses to disturbance, invertebrates are invaluable for evaluating ecosystem health and identifying

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disturbed habitats (Gesteira and Dauvin, 2000; Guerra-Garcia and Garcia-Gomez, 2004; Pearson and Rosenberg, 1978). Invertebrates have been used to develop ecological theories on organismal responses to disturbance (Cowie et al., 2000; Gerwing et al., 2017a; Pearson and Rosenberg, 1978), and are employed in both monitoring and assessing human impacts on natural ecosystems (Borja and Muxika, 2005; Gerwing et al., 2018a; Hereward et al. 2017; Muxika et al. 2005; Pearson and Rosenberg, 1978). In addition to monitoring applications, marine benthic invertebrates support commercial fisheries, both by serving as dietary sources for fish and as industrial bait (Davis et al., 2014; Kritzer et al., 2016; Pires et al., 2017). Therefore, studying invertebrates is a pro-active strategy to detect disturbances before productivity of commercial fisheries is impaired (Ozdemir et al., 2011; Pinto et al., 2009). In soft-sediment ecosystems, infaunal invertebrates have been employed as successful indicators for multiple disturbance mechanisms including organic enrichment, hypoxia, and pollution (Bett, 1988; Pearson and Rosenberg, 1978; Thrush et al., 2003).

Although disturbance can have detrimental effects, soft-sediment ecosystems and infaunal communities are resilient to disturbance as the fauna are exposed to extreme variability on a daily basis (Altieri, 2006; Cowie et al., 2000; Gerwing et al., 2018a; Valdivia et al., 2011), and are responsive to passive reclamation through both physical and biological processes such as wave action, sediment deposition, and bioturbation (Dernie et al., 2003; Gerwing et al., 2018a; Skilleter, 1996). Passive reclamation is the cessation of activities causing ecosystem degradation, thus allowing for unassisted recovery (Benayas et al., 2009; Holl and Aide, 2011). Considered to be the first and most crucial step in ecological reclamation, passive reclamation can be highly effective in coastal and estuarine ecosystems without the associated cost of active reclamation; however, not all reclamation efforts track progress against recovery targets, or consider infaunal communities (Bayraktarov et al., 2016; Holl and Aide, 2011; Kauffman et al., 1997; Marquiegui and Aguirrezabalaga, 2009; McCrackin et al., 2017).

Along the North Coast of British Columbia (BC) Canada, the Skeena River estuary has experienced a variety of disturbances, including physical disruption of soft-sediment, organic enrichment, and accumulation of toxins (Carr-Harris et al., 2015; Gerwing et al. 2018a). Near the mouth of the Skeena River, the mudflat surrounding Cassiar Cannery in Inverness Passage (Fig. 1) experiences physical disturbance to the sediment from logs that are transported down the Skeena River, flow through Inverness Passage, and accumulate on the mudflat, while an old dock structure may deposit woody debris into the sediment, potentially resulting in organic enrichment. However, in addition to these current impacts, this mudflat has also been undergoing passive reclamation from historical activities. Established in 1889, Cassiar Cannery was the longest consecutively operating salmon cannery on BC's coast before closing in 1983, with associated disturbances including toxic inputs like copper and creosote, and organic enrichment from discarded salmon carcasses (Beyer et al., 1975; Faggetter, 2008; Stone et al., 1981). Furthermore, through the 1900s, 12 salmon canneries operated near the mouth of the Skeena River, with the last cannery ceasing operation in 1989, while pulp mill operations commenced in the 1970s and continued through 2001(Akenhead, 1992; Faggetter, 2008; Yunker et al., 2002). Unfortunately, estuarine and coastal ecosystems may require at least 15–25 years to recover from degradation spanning a century, or alternatively may never recover and instead exist in a perpetual alternate state (Borja et al., 2010; McCrackin et al., 2017; Simenstad et al., 2006). Therefore, considering historical impacts is crucial when assessing estuary health and ecosystem functioning (Szabo, 2010).

At the Cassiar Cannery mudflat, the sediment is predominantly fine silt ($< 63\,\mu$m) and fine-grained sand (125–250 μm) with coarser grain sand and pebbles present within small patches. A 1–3 mm layer of oxic mud occurs at the sediment surface (Gerwing et al., 2017a; McLaren, 2016). The mudflat was sampled at four distinct locations (Fig. 1), with two locations considered impacted (hereafter referred to as Resort and Dock locations) and two chosen as reference stations. As both the Resort Location and Dock Location are within the historical footprint of the salmon cannery, they were thus historically impacted via chemicals such as creosote, copper and copper soldering products, pyrogenic polycyclic aromatic hydrocarbons, grease and other chemicals (Faggetter, 2008; Page et al., 1999). Substantial nutrient inputs also occurred due to salmon carcass discards (Beyer et al., 1975; Stone et al., 1981). The Dock Location (DL) is situated below the historical wooden dock and is hypothesized to be currently impacted by the dock depositing woody debris on the mudflat surface. Additionally, the benthos below the dock has not seen direct sunlight for ~130 years, and sedimentation and hydrology are likely affected by the physical structure of the dock. The Resort Location (RL) is in front of former homes of cannery managers that have been restored to heritage houses, allowing Cassiar Cannery to continue operating as an ecotourism resort. This study does not examine impacts of the resort itself, but instead looks at the current physical disturbance to the sediment surface that occurs at the Resort Location from accumulated logs that flow from the Skeena River through Inverness Passage and scour the sediment surface (Gerwing et al., 2015a; Herbert et al., 2009).

The majority of mudflats in the region had salmon canneries operating on them, greatly decreasing the availability of reference locations within the immediate region that reflect unimpacted soft-sediment ecosystems. The reference locations employed (North Reference (NR) and South Reference (SR)) are both outside the area of current impacts of physical disturbance from logs and the dock structure, and are also outside the historical footprint of the salmon cannery. Due to high tidal flushing, as well as water and sediment input from the Skeena and Nass Rivers (McLaren, 2016) any organic matter or chemicals present would likely have been diluted and had minor impacts upon the reference locations (Beyer et al., 1975). Therefore, these locations are adequate reference locations (Underwood, 1994, 1997, 2009).

By employing these four study locations, this study attempts to reveal current impacts regarding organic enrichment and physical disturbance from potential woody debris deposition and log scour at the intertidal mudflat surrounding Cassiar Cannery, while also considering historical impacts and the trajectory of passive reclamation. To accomplish these goals, the infaunal community, sediment parameters and nutrient availability were examined at reference and potentially impacted locations. Within the infaunal community, high abundances of indicator taxa including oligochaetes, nematodes, and polychaetes from the families Spionidae and Capitellidae may indicate impacted habitat, as these taxa are often found in higher abundances in disturbed habitats (Chollett and Bone, 2007; Pearson and Rosenberg, 1978), and these were thus hypothesized to be present at higher abundances at the Dock and Resort Locations. Conversely, taxa indicating healthy habitats such as amphipods and mobile, errant polychaetes were expected to be absent from disturbed locations (Cardoso et al., 2007; Gesteira and Dauvin, 2000). The dock was also expected to decrease the depth to the apparent redox potential discontinuity depth (aRPD), due to increased oxygen consumption during decomposition of woody debris, with a subsequent increase in organic matter content at the Dock Location (Kristensen, 2000; Pearson and Rosenberg, 1978). Impacted locations were also expected to have reduced primary productivity due to disruption to biotic structures and the dock reducing light availability. A greater understanding of passive reclamation and its efficacy would help to inform cost-benefit decisions of coastal management and reclamation activities, given the high costs associated with active reclamation.

2. Methods

2.1. Sampling scheme and field methods

At each location three transects were established, stretching from the start of the mudflat to the low tide waterline (Cox et al., 2017; Gerwing et al., 2015b). Transects were 60 m long, placed 10 m apart, and stratified into three equal zones based upon distance from shore (near, middle, far). Within each zone, a 1m^2 quadrat was randomly

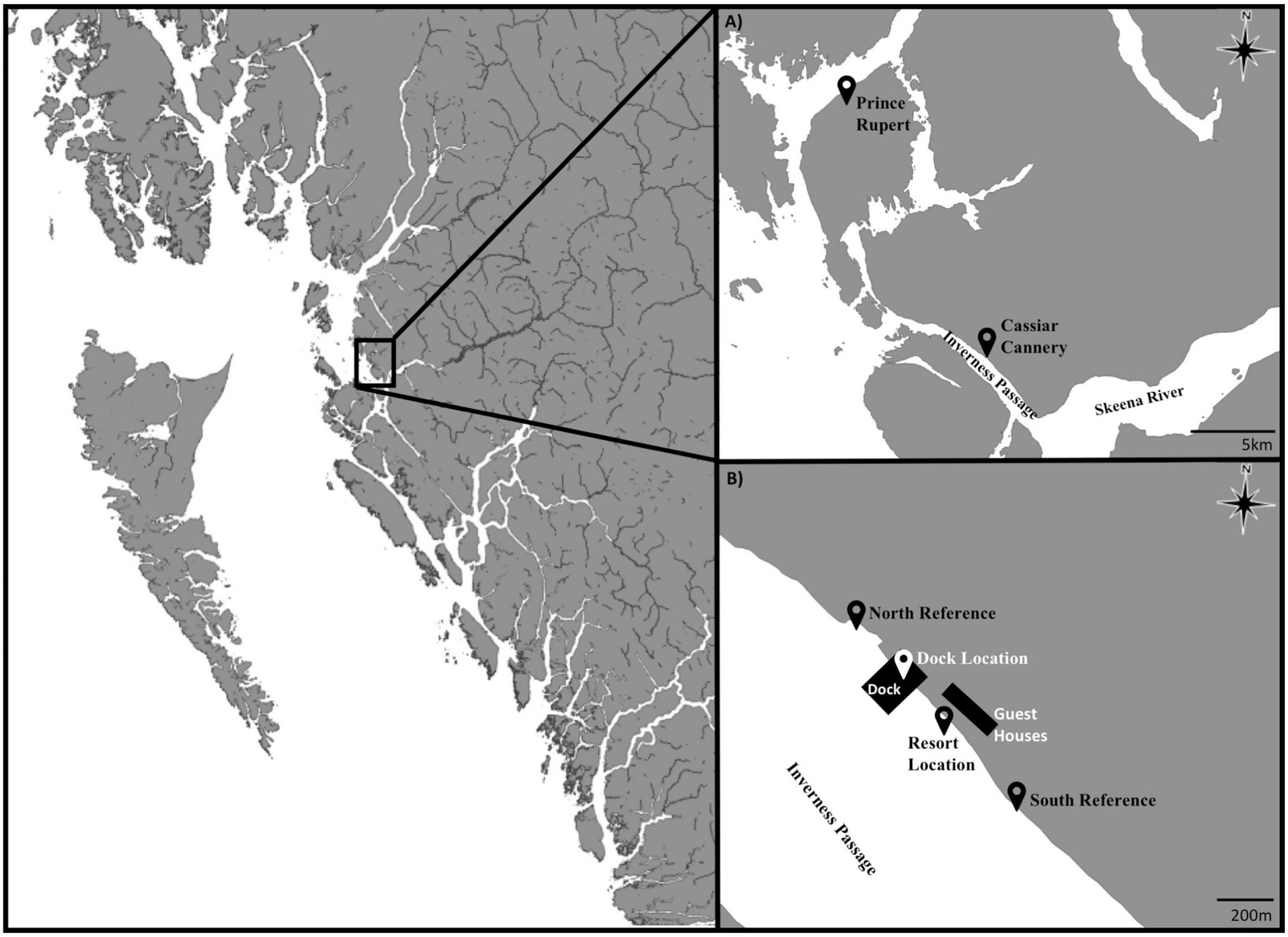

Fig. 1. Location of the Cassiar Cannery mudflat (54.178092°, −130.176924°) sampled during summer 2017, in Inverness Passage, British Columbia, Canada. A) shows the location of the Cassiar Cannery mudflat within Inverness Passage relative to the Skeena River and Prince Rupert. B) shows the 4 locations sampled on the Cassiar Cannery mudflat. DL: Dock Location (benthos underneath the dock denoted by DK), RL: Resort Location (in front of guest houses denoted by GH), NR: North Reference, SR: South Reference.

selected and established ($n = 3$ per transect, 9 per location). All 4 locations were sampled in a day, 3 times throughout the summer of 2017 (May 30, June 21, and July 20) at the lowest low tides (Cox et al., 2017; Gerwing et al., 2017a) for a total of 27 sampling events per location.

At each 1m^2 quadrat, infauna was collected with a core of 10 cm in length and a diameter of 7 cm. Following collection, the sediment was passed through a 250 μm sieve and stored in vials of 95% ethanol (Bringloe et al. 2013; Gerwing et al., 2017a; Hamilton et al. 2006; Sizmur et al., 2019). Forty infaunal taxa have previously been identified at the Cassiar Cannery (Gerwing et al., 2017a; Gerwing et al. 2018c), and specimens were identified to the lowest possible taxonomic unit (Gerwing et al., 2017a; Thrush et al., 2003) as follows: cumaceans, amphipods, polychaetes, nemerteans and bivalves were identified to species; chironomids (larvae) to family; copepods to order; ostracods to class; and nematodes to phylum.

For sediment parameters, surface wood cover (%) and macrophyte cover (%) of the quadrat were visually estimated, and sediment penetrability was assessed by dropping a metal weight (15 cm long, 1.9 cm diameter, 330 g) from a height of 0.75 m above the sediment (Gerwing et al., 2015b). The depth the weight penetrated the sediment was measured as an indication of how easily water and animals can penetrate the sediment, therefore generating an index that can be compared between quadrats and locations. Additionally, water content, and volume weighted mean particle size in the upper 1 cm of sediment were quantified as outlined in Gerwing et al. (2015b) by collecting a sediment core (4.5 cm diameter, 5 cm length) from each quadrat. The top 1 cm of each core was weighed, placed in a drying oven at 110 °C for 12 h, and re-weighed. Percent water-content was calculated as:

$$(\text{Mass wet sediment–mass dry sediment})/(\text{mass wet sediment}) \times 100$$

Volume-weighted mean particle-size of the sediment for each sample was determined using a Malvern Mastersizer 2000 (www.malvern.com). Particle size was measured in triplicate and a mean value per sample calculated (Gerwing et al., 2015b).

Depth of the apparent redox potential discontinuity (aRPD) was measured to the nearest 1 mm as an index of sediment dissolved oxygen content (Gerwing et al., 2017b; Gerwing et al., 2015c). aRPD depth gives a relative measure of sediment dissolved oxygen content and redox conditions. The aRPD was measured in the sediment void left by the removal of the 7 cm diameter infauna core (Gerwing et al., 2013).

Organic matter content was quantified from the sediment core as outlined by Gerwing et al. (2015b). Briefly, dried sediment samples were ashed in a muffle furnace at 550 °C for four hours and re-weighed. Percent organic-content was calculated as:

$$(\text{Mass dry sediment–mass of ashed sediment})/(\text{mass of dry sediment}) \times 100$$

Chlorophyll *a* concentration was used as a proxy for the abundance of benthic diatoms (Coulthard and Hamilton, 2011; Hargrave et al., 1983; Trites et al., 2005). A 2 cm diameter core was taken to determine the concentration of chlorophyll *a* in the top 2–3 mm of sediment as

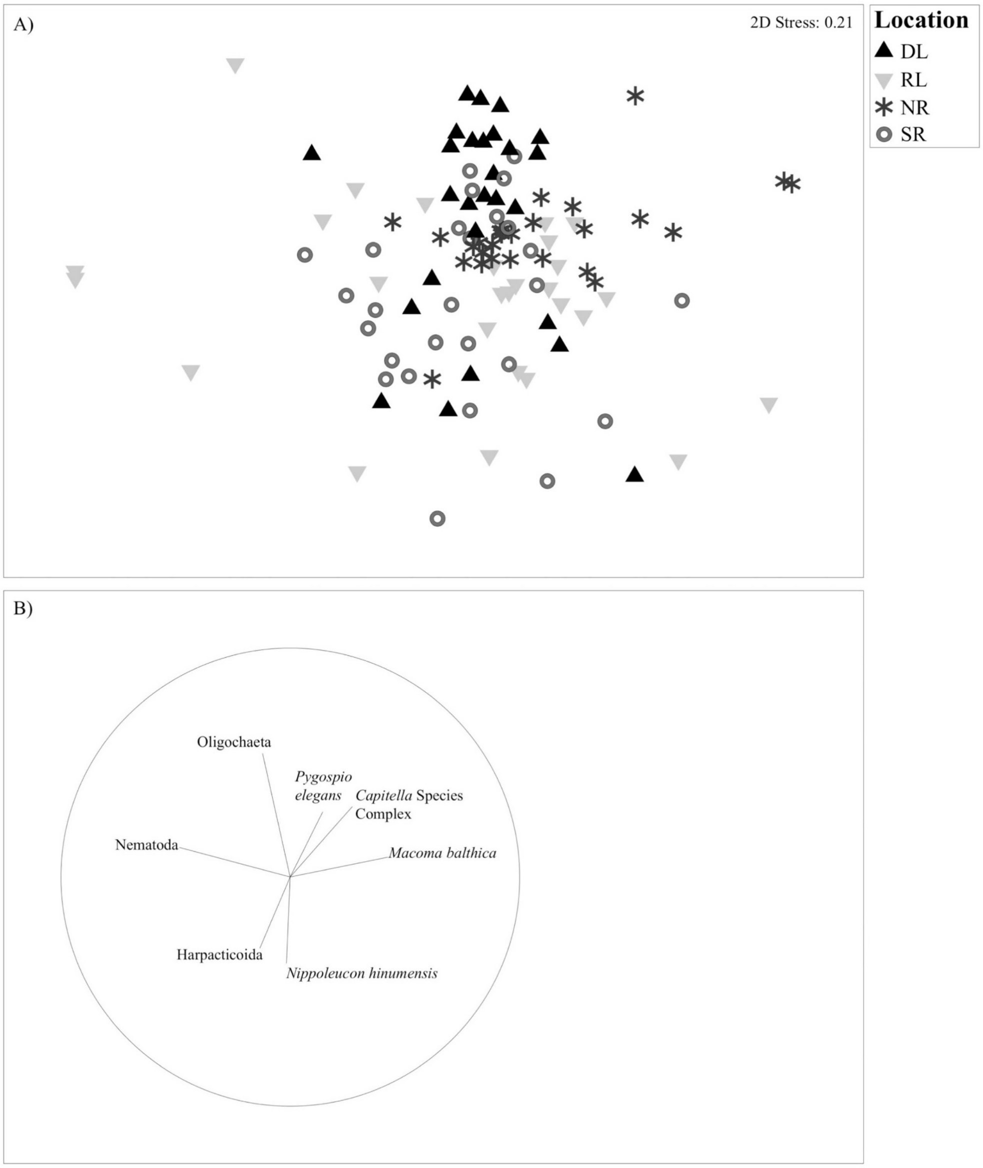

Fig. 2. Non-metric multidimensional scaling (nMDS) graphs showing infaunal invertebrate community at four locations on the intertidal mudflat at Cassiar Cannery in Inverness Passage, British Columbia, during the summer of 2017. A) the infaunal community by location and B) the vector overlay indicates the direction of increased density, with correlations > 0.3 shown. DL: Dock Location. RL: Resort Location. NR: North Reference. SR: South Reference.

outlined by Coulthard and Hamilton (2011). Briefly, chlorophyll pigments were extracted from sediment samples via buffered acetone (90%) and processed through a spectrophotometer to assess reflectance of chlorophyll pigments (664 and 750 nm).

2.2. Statistical analysis

The Permutational Multivariate Analysis of Variance (PERMANOVA) package in the statistical program PRIMER 7 (McArdle and Anderson 2001; Clarke and Gorley 2015) was used to elucidate how biotic and abiotic parameters varied between reference and impacted locations. These parameters were divided into infaunal community (species composition and abundance), sediment parameters (depth to the aRPD, sediment water content, volume weighted mean particle size, penetrability, % macroalgae coverage, and % wood coverage), and nutrient variables (chlorophyll *a* concentration and sediment organic matter). Groups of variables were then analyzed separately, to elucidate any differences between reference and potentially impacted areas.

Infaunal abundances were fourth root ($x^{1/4}$) transformed to decrease the importance of very abundant species on the outcome of analyses and improve the assessment of less common species. Subsequently, Bray-Curtis distances were used to create a resemblance matrix (Clarke et al. 2006) for the PERMANOVA. Within this PERMANOVA, Location (4 levels), and Sampling Date (3 levels) were fixed factors, while Transect nested within Location (Transect(Location); 3 levels) was a random factor. Four a priori planned contrasts examined how locations varied from each other as follows: 1) Dock Location (DL) vs. reference locations (NR + SR); 2) Resort Location (RL) vs. reference locations (NR + SR); 3) DL vs. RL; and 4) NR vs. SR. An α of 0.05 denotes statistical significance for all analyses. A PERMANOVA was also run to determine if taxonomic richness varied between impacted and reference locations, by summing the number of taxa observed at each quadrat, with Bray-Curtis distances for the resemblance matrix. Taxonomic richness was used as not all specimen could be identified to species, therefore richness is not a true measure of species richness, instead it measures the number of observed taxa (Gerwing et al. 2016; Gerwing et al., 2015b).

For the sediment PERMANOVA, depth to the aRPD, volume-weighted mean sediment size, % macroalgae cover and % wood cover were square root (√x) transformed to correct for skewed distributions. For the nutrient matrix, all variables were square root (√x) transformed. All variables were normalized, and Euclidean distances were used to calculate a resemblance matrix. Factors and planned contrasts for both the sediment and nutrient PERMANOVA were as described above in the infauna PERMANOVA. Sediment variables also had an a priori analysis conducted for Date X Location comparisons.

Similarity Percentages analyses (SIMPER; Clarke 1993) were used to examine the contribution of each variable (infaunal, sediment or nutrient) to the observed differences between locations or sampling dates. Increased percent dissimilarity indicates increased dissimilarity between locations. The ratio of each variable's average dissimilarity to the standard deviation of dissimilarities (Diss/SD) for infauna, or average squared Euclidean distance to the standard deviation of squared distances (Sq.Dist/SD) for sediment and nutrient variables were calculated. These values represent how consistently each variable contributed to the observed difference; variables with a ratio > 1 consistently contributed whereas those with a value below 1 did not (Gerwing et al., 2015b). Finally, non-metric multidimensional scaling (nMDS, 100 restarts) plots were used to visualize variation in infauna, sediment conditions, and nutrient availability between locations. All nMDS graphs had a stress of ~ 0.2, and were considered to be good two-dimensional representations (Clarke 1993).

3. Results

Analysis of the invertebrate community and sediment variables through PERMANOVAs showed statistically significant spatiotemporal variation, while nutrient availability varied significantly through time (Figs. 2-3; Tables 1-2; Supplemental Material Tables 1-3). Both the infauna community and sediment parameters varied significantly between impacted locations (Dock and Resort Locations) and reference locations (North and South Reference; Table 1). Percent dissimilarity of the infaunal community between locations varied between 44 and 52% (Table 3). A large proportion of the variation in dissimilarity of location comparisons was driven by four taxa: Oligochaeta, *Pygospio elegans, Capitella* Species Complex and Nematoda (40–45%; Table 3). However, taxa contributing to observed differences between locations varied. Nematoda, Oligochaeta, and *P. elegans* were consistently more abundant at DL (7.00, 5.55 and 6.08 individuals/m^2 respectively) compared to reference locations (6.10, 3.23 and 4.71 individuals/m^2), but these taxa were consistently higher at reference locations compared to RL (4.74, 1.07 and 4.57 individuals/m^2). Furthermore, *Capitella* Species Complex was consistently higher at reference locations (5.49 individuals/m^2) than either disturbed location (3.71 and 3.70 individuals/m^2) (Table 3). The amphipod *Americorophium salmonis* was present at higher abundances in reference locations compared to the Dock Location (4.76 Vs 2.66), but at lower abundances compared to the Resort Location (4.82) (Table 3). The errant polychaete *Eteone californica* was also present in high abundances at each location with average abundances at DL, RL, and the reference locations being 2.49, 2.90 and 4.07 respectively. Taxonomic richness did not vary significantly with either location or date ($p = 0.5298$ and 0.0950 respectively; Table 1).

A significant interaction was found for Date and Location factors of sediment parameters, therefore a priori contrasts were conducted for each location and sampling date comparison. Sediment properties varied significantly for all location comparisons, except between reference locations (NR vs SR; Table 2). Wood cover contributed the most to location comparisons including DL; however it only consistently contributed for the June 21 sampling date as shown by the Sq.Dist/SD ratio > 1 (Table 4). No other trend was observed, and average squared distance for location comparisons ranged from 12.29–14.42.

Nutrient availability had significant differences between sampling dates ($p = 0.0002$), but with no observed effect of location on availability (Table 1). Neither chlorophyll *a* concentration nor organic matter content consistently contributed to the differences between sampling dates (Table 5). Average squared distance between sampling dates was between 2.28 and 5.18.

4. Discussion

Along the North Coast of British Columbia, Canada, the intertidal mudflat surrounding Cassiar Cannery may be impacted from current disturbances including physical disruption of the sediment from logs and a dock structure depositing woody debris on the substrate. Simultaneously, this mudflat is also undergoing passive reclamation from historical impacts associated with salmon canneries and a pulp mill. Therefore, the objective of this study was to examine current impacts while considering historical impacts in the region with regards to the infaunal community, sediment conditions, and nutrient availability.

4.1. Infaunal community

With regards to community composition, there was conflicting evidence of disturbance and of overall health at different spatial scales. The infaunal community exhibited significant spatiotemporal variation, with the presence of oligochaetes, nematodes, and polychaetes from the families Spionidae and Capitellidae, as well as low abundances of amphipods indicative of current or historic disturbances (Chollett and Bone, 2007; Keats et al., 2004; Kesaniemi et al., 2012; Pearson and Rosenberg, 1978). The infaunal community under the dock (DL) was characterized by higher abundances of oligochaetes, nematodes, and Spionidae polychaetes when compared to the reference locations, as well as by smaller populations of amphipods. Furthermore, DL had an increased abundance of *Nippoleucon hinumensis* than reference areas which could be indicative of disturbance, as *N. hinumensis* is an invasive cumacean from Asia (Light and Smith, 2007) and disturbance can facilitate biological invasions (Burke and Grime, 1996; Smith and Knapp, 1999). These community characteristics are all representative of a disturbed habitat, and it is unsurprising that the dock is altering the infaunal community composition beneath it. Conversely, the mudflat in front of the ecotourism resort (RL) had smaller populations of oligochaetes, nematodes, and Spionidae and Capitellidae polychaetes, as well as higher populations of amphipods when compared to reference locations. As such, there is no evidence that the mudflat in front of the ecotourism lodge (RL) is negatively impacted by log scour or by the activities of the lodge itself. Moreover, no differences in taxonomic richness were revealed between impacted or reference locations, further suggesting that the potentially disturbing agents occurring at the Cassiar Cannery are not impacting the mudflat.

Interestingly, reference locations had higher average abundances of Capitellidae polychaetes when compared to the dock (DL) and resort (RL) locations. This was unexpected, as Capitellidae polychaetes can be indicative of disturbance, particularly of organic enrichment that was expected to occur under the dock structure (Pearson and Rosenberg, 1978). However, and as discussed in detail below, no organic enrichment under the dock was observed. Further, Capitellidae polychaete abundance in all locations on the Cassiar Cannery mudflat were similar to those observed on non-organically enriched mudflats in the region (Campbell et al., 2019) as well as on mudflats on the Atlantic coast (Gerwing et al., 2015b). Therefore, Capitellidae polychaetes were within normal abundances when considering the scale of the entire mudflat.

Beyond contrasting different locations within the Cassiar Cannery mudflat, some inferences can be made regarding the overall health of this mudflat. First, all locations had high populations of mobile errant polychaetes and amphipods. Amphipods and mobile errant polychaetes are powerful indicator species (Cardoso et al., 2007; Conlan, 1994; Gerwing et al., 2018a; Gerwing et al., 2018b; Gesteira and Dauvin, 2000; Thomas, 1993), whose high densities throughout this mudflat suggest that the Cassiar Cannery mudflat is relatively healthy. Additionally, complex community structure with multiple species present

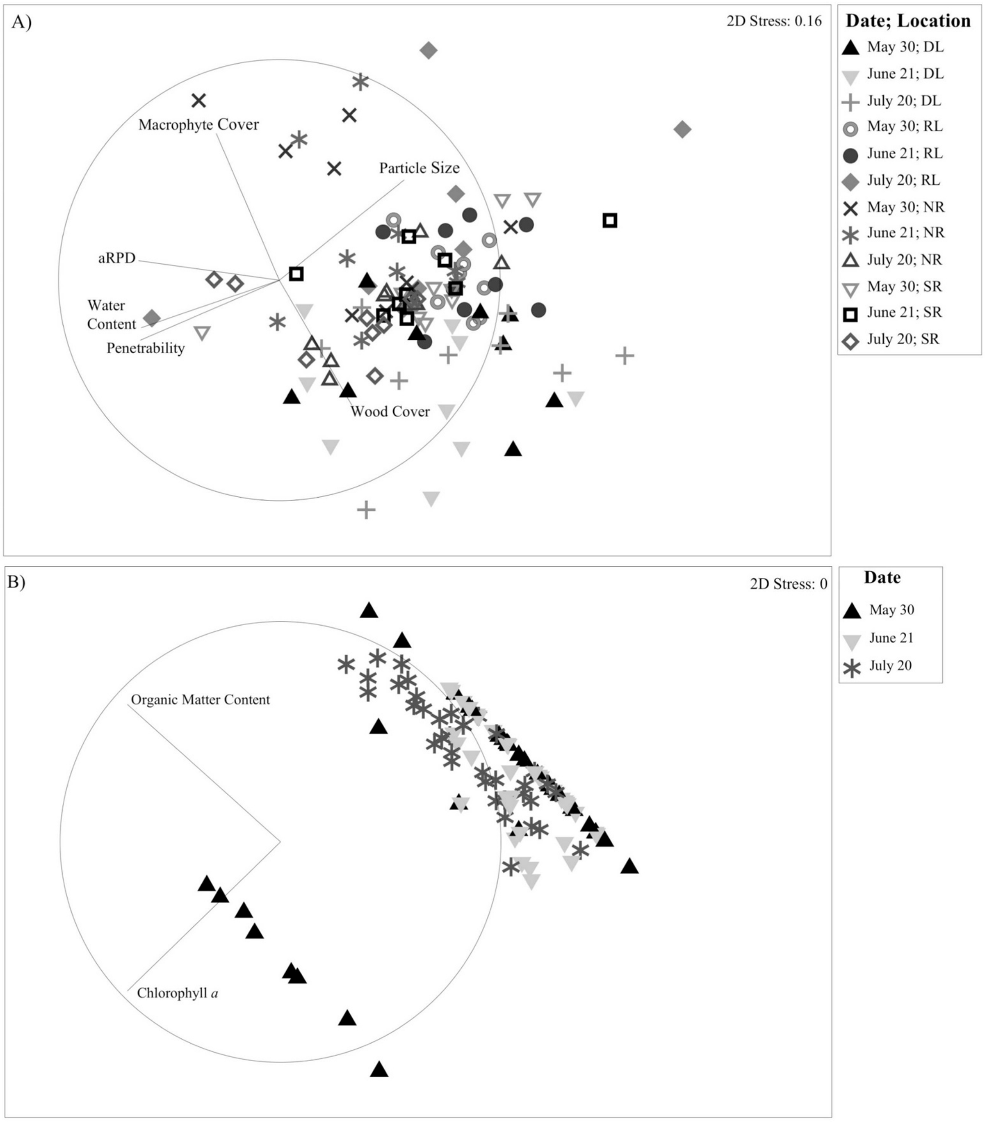

Fig. 3. Non-metric multidimensional scaling (nMDS) graphs of A) sediment parameters (depth to the aRPD, water content, particle size, penetrability, % macroalgae coverage, and % wood cover) by time and location and B) the nutrient availability (chlorophyll *a* and organic matter content) at four locations on the intertidal mudflat at Cassiar Cannery in Inverness Passage, British Columbia, during the summer of 2017. Vector overlays for sediment and nutrient variables show the correlation between variables and nMDS axes, with each vector showing the direction of increased value. DL: Dock Location. RL: Resort Location. NR: North Reference. SR: South Reference.

at all levels of the food web, coupled with high biodiversity is also often representative of relatively undisturbed and/or functional habitats (Pearson and Rosenberg, 1976; Pearson and Rosenberg, 1978). With high biodiversity, and a complex community across trophic levels, the Cassiar Cannery mudflat has a diverse and functioning food web and as such the community structure is similar to undisturbed mudflats (Cardoso et al., 2007; Gerwing et al., 2015b; Gesteira and Dauvin, 2000; Hooper et al., 2005).

While at the scale of the mudflat, Cassiar Cannery may be relatively healthy and functional, community composition at the spatial scale of the 1m^2 quadrat offers a slightly contradictory perspective. Invasive Cumacea, Capitellidae and Spionidae polychaetes, oligochaetes, and nematodes were observed in some quadrats in all locations at densities indicative of disturbance (Chollett and Bone, 2007; Keats et al., 2004; Kesaniemi et al., 2012; Pearson and Rosenberg, 1978). While this could be the result of natural variability, previous investigations of infaunal community composition along BC's north coast have detected remnant signals of historical disturbances within relatively healthy mudflats decades after disturbance (e.g. logging practices (Gerwing et al., 2018b)). It is hypothesized that a similar phenomenon may have been observed here. Within Inverness Passage, 3 salmon canneries besides Cassiar were operating, and another 8 operated around the mouth of the Skeena River (Hoos, 1975). Furthermore, a pulp mill in the region discharged highly toxic effluents and spent sulfite liquid (500 tons/day) into the nearshore environment commencing in the 1970s (Hoos, 1975; Waldichuk, 1966; Wilkes and Dwernychuk, 1991). The decomposition of the spent sulfite liquid led to greatly reduced biological oxygen demand, and the effluent accumulated in a three-meter thick layer of toxic sludge on the littoral zone near the discharge pipe. Although the discharge pipe was moved in the early 1990s before the mill ceased operations in 2001, much of the invertebrate community was defaunated by effluents (Akenhead, 1992; Hoos, 1975; Waldichuk, 1966). Therefore, while the Cassiar Cannery mudflat is now overall relatively healthy, biological signals of disturbance at the scale of the 1m^2 quadrat may be remnants of the historical disturbances this mudflat has experienced. Cessation of disturbances associated with the pulp mill and canneries would have allowed for the process of passive reclamation, which appears to have been relatively successful for this infaunal community.

Table 1
Permutational multivariate analysis of variance (PERMANOVA) quantifying the spatiotemporal variation in A) infaunal invertebrate community, and B) taxonomic richness, and C) sediment parameters, and D) the nutrient parameters at four locations at the intertidal mudflat at Cassiar Cannery during the summer of 2017.

Source	df	MS	Pseudo-F	Unique Permutations	p
(A)					
Date	**2**	**6939.90**	**6.93**	**4982**	**0.0002**
Location	**3**	**6316.20**	**3.38**	**4237**	**0.0002**
DL vs (NR + SR)	**1**	**6973.10**	**6.95**	**4986**	**0.0002**
RL vs (NR + SR)	**1**	**5798.70**	**4.69**	**4992**	**0.0008**
DL vs RL	**1**	**7738.00**	**5.97**	**4990**	**0.0002**
NR vs SR	**1**	**5500.80**	**5.81**	**4986**	**0.0002**
Transect(Location)	**8**	**1869.20**	**2.11**	**4971**	**0.0002**
Date X Location	6	1345.20	1.34	4978	0.1550
Date X Transect (Location)	16	1001.50	1.13	4958	0.2372
Residual	72	885.96			
Total	107				
(B)					
Date	2	435.28	2.13	4990	0.0950
Location	3	1004.20	0.90	4225	0.5298
Transect(Location)	**8**	**1121.80**	**4.57**	**4975**	**0.0002**
Date X Location	6	244.31	1.19	4988	0.3290
Date X Transect (Location)	16	204.67	0.83	4978	0.6982
Residual	72	245.43			
Total	107				
(C)					
Date	2	4.58	1.29	4974	0.2670
Location	**3**	**35.72**	**5.48**	**4248**	**0.0004**
Transect(Location)	8	6.52	1.25	4977	0.1486
Date X Location	**6**	**6.96**	**1.96**	**4982**	**0.0278**
Date X Transect (Location)	16	3.55	0.68	4961	0.9826
Residual	72	5.21			
Total	107				
(D)					
Date	**2**	**9.76**	**11.49**	**4989**	**0.0002**
May 30 vs June 21	**1**	**7.74**	**8.79**	**4987**	**0.0002**
May 30 vs July 20	**1**	**6.77**	**3.50**	**4987**	**0.0306**
June 21 vs July 20	**1**	**15.85**	**8.79**	**4987**	**0.0002**
Location	3	2.35	1.12	4258	0.4162
Transect(Location)	8	2.10	0.99	4983	0.4696
Date X Location	6	0.69	0.81	4980	0.6526
Date X Transect (Location)	16	0.85	0.40	4967	0.9976
Residual	72	2.12			
Total	107				

DL: Dock Location. RL: Resort Location. NR: North Reference. SR: South Reference. Significant *p* values ($\alpha < 0.05$) are denoted in bold.

4.2. *Sediment parameters*

Sediment parameters varied significantly through time and space, including in comparisons between impacted and reference locations, but no variable consistently contributed to location differences. Wood cover had the largest percent contribution for all comparisons including the Dock Location (18.9–27.0%), but only consistently contributed for one sampling date (June 21). It was hypothesized that the accumulation of woody debris at DL would decrease the depth to the aRPD as oxygen is consumed during the degradation of woody debris. However, this was not observed and may be due to tidal flushing either replenishing oxygen consumed in decomposition or removing woody debris before it has sufficient time to decompose (Kristensen, 2000). Evidence suggests the latter, as organic matter content was not significantly higher at DL compared to the other locations. Interestingly, DL was the only location that had no macroalgae cover for any quadrat on any sampling date (Supplemental Material Table 2), which may indicate that the dock structure is affecting the hydrology and light availability at the Dock Location.

Table 2
Permutational multivariate analysis of variance (PERMANOVA) quantifying the spatiotemporal variation in sediment variables on three sampling dates at the Cassiar Cannery intertidal mudflat during the summer of 2017. Date was run as separate PERMANOVAs due to the significant interaction term between Date X Location in Table 1.

Source	df	MS	Pseudo-F	Unique Permutations	*p*
May 30					
Location	**3**	**14.32**	**3.37**	**4269**	**0.0008**
DL Vs (NR + SR)	**1**	**16.48**	**2.95**	**4989**	**0.0128**
RL Vs (NR + SR)	**1**	**15.11**	**2.68**	**4985**	**0.0214**
DL Vs RL	**1**	**12.56**	**2.25**	**4516**	**0.0328**
NR Vs SR	1	13.13	2.36	4483	0.0800
Transect(Location)	8	4.25	0.77	4969	0.8500
Residual	24	5.54			
Total	35				
June 21					
Location	**3**	**18.83**	**4.06**	**4238**	**0.0008**
DL Vs (NR + SR)	**1**	**26.10**	**5.02**	**4983**	**0.0002**
RL Vs (NR + SR)	**1**	**17.50**	**3.16**	**4986**	**0.0084**
DL Vs RL	**1**	**27.39**	**5.87**	**4468**	**0.0002**
NR Vs SR	1	5.69	0.94	4503	0.4700
Transect(Location)	8	4.64	0.96	4967	0.5600
Residual	24	4.85			
Total	35				
July 20					
Location	**3**	**14.68**	**2.75**	**4245**	**0.0032**
DL Vs (NR + SR)	**1**	**23.23**	**4.37**	**4979**	**0.0020**
RL Vs (NR + SR)	**1**	**12.20**	**2.12**	**4978**	**0.0438**
DL Vs RL	**1**	**15.49**	**2.87**	**4533**	**0.0058**
NR Vs SR	1	8.63	1.48	4517	0.1700
Transect(Location)	8	5.33	1.04	4958	0.4200
Residual	24	5.14			
Total	35				

DL: Dock Location. RL: Resort Location. NR: North Reference. SR: South Reference. Significant p values ($\alpha < 0.05$) are denoted in bold.

As physical disturbance can disrupt the redox potential discontinuity and result in water accumulation in associated pits and furrows (Dernie et al., 2003), changes to the aRPD depth and water content were potential indicators of physical disturbance at the Resort Location due to scour by logs. However, this was not observed in this location, as neither the aRPD depth nor water content consistently contributed to differences in sediment variables between RL and other location comparisons. Additionally, mudflats show high spatiotemporal variation in their sediment parameters (Gerwing et al., 2015b), suggesting that the variability present on this mudflat may not be a result of current or historical impacts.

4.3. *Nutrient availability*

Although the biological community and sediment conditions showed significant spatiotemporal variation, nutrient availability (chlorophyll *a* concentration and percent organic matter) only showed temporal variation. Both chlorophyll *a* and organic matter content are known to vary through time, so temporal differences were not surprising (Gerwing et al., 2015b; Hargrave et al., 1983; Trites et al., 2005). However, a lack of spatial variation was unexpected. As the Dock Location receives no direct sunlight, it was hypothesized to have the lowest chlorophyll *a* concentration, yet this was not observed. Some species of microalgae can acclimatize to shade (Katayama et al., 2018), and cyanobacteria can produce more chlorophyll *a* at low light

Table 3
SIMPER (Similarity Percentages) determining the contribution of each taxonomic grouping to the observed differences between intertidal locations at Cassiar Cannery in Inverness Passage during summer of 2017.

DL vs (NR + SR)							RL vs (NR + SR)						
Average Dissimilarity = 45.90%	DL	(NR + SR)					Average Dissimilarity = 50.09%	RL	(NR + SR)				
Species	Abundance	Abundance	Av.Diss	Diss/SD	Contribution (%)	Cumulative (%)	Species	Abundance	Abundance	Av.Diss	Diss/SD	Contribution (%)	Cumulative (%)
Oligochaeta	**5.55**	**3.23**	**5.01**	**1.23**	**10.91**	**10.91**	***Capitella* Species Complex**	**3.71**	**5.49**	**5.95**	**1.18**	**11.88**	**11.88**
Pygospio elegans	**6.08**	**4.71**	**4.85**	**1.19**	**10.56**	**21.47**	**Nematoda**	**4.74**	**6.10**	**5.87**	**1.18**	**11.72**	**23.59**
Nematoda	**7.00**	**6.10**	**4.55**	**1.13**	**9.91**	**31.38**	***Pygospio elegans***	**4.57**	**4.71**	**5.41**	**1.20**	**10.80**	**34.39**
Harpacticoida	**1.06**	**4.03**	**4.38**	**1.24**	**9.54**	**40.93**	***Americorophium salmonis***	**4.82**	**4.76**	**5.00**	**1.14**	**9.98**	**44.37**
Americorophium salmonis	**2.66**	**4.76**	**4.23**	**1.27**	**9.22**	**50.15**	***Macoma balthica***	**3.60**	**4.68**	**4.54**	**0.98**	**9.06**	**53.43**
***Capitella* Species Complex**	**3.70**	**5.49**	**4.15**	**1.20**	**9.05**	**59.19**	***Eteone californica***	**2.90**	**4.07**	**4.21**	**1.09**	**8.40**	**61.82**
Nippoleucon hinumensis	**2.79**	**2.27**	**3.61**	**1.05**	**7.86**	**67.05**	**Oligochaeta**	**1.07**	**3.23**	**4.16**	**1.08**	**8.30**	**70.13**
Eteone californica	**2.49**	**4.07**	**3.35**	**1.12**	**7.30**	**74.35**	Harpacticoida	3.37	4.03	4.12	0.96	8.22	78.35
Aricidea hartleyi	2.29	0.07	2.55	0.79	5.56	79.91	*Nippoleucon hinumensis*	1.76	2.27	3.56	0.94	7.11	85.45
Macoma balthica	4.99	4.68	2.45	0.94	5.34	85.26	*Cumella vulgaris*	1.13	0.45	1.90	0.62	3.79	89.25
Cumella vulgaris	1.67	0.45	2.13	0.78	4.64	89.90	Chironomidae Larvae	0.99	0.00	1.34	0.49	2.68	91.93
Paranemertes peregrina	0.66	0.81	1.38	0.61	3.00	92.90	*Paranemertes peregrina*	0.18	0.81	1.12	0.49	2.24	94.17
Abarenicola pacifica	0.18	0.85	1.06	0.48	2.31	95.21	*Abarenicola pacifica*	0.00	0.85	1.07	0.43	2.14	96.31
Ostracoda	0.30	0.32	0.76	0.39	1.66	96.87	Ostracoda	0.15	0.32	0.67	0.32	1.35	97.65
Fabricia stellaris	0.41	0.13	0.51	0.31	1.10	97.97							

DL vs RL							NR vs SR						
Average Dissimilarity = 52.98%	DL	RL					Average Dissimilarity = 44.17%	NR	SR				
Species	Abundance	Abundance	Av.Diss	Diss/SD	Contribution (%)	Cumulative (%)	Species	Abundance	Abundance	Av.Diss	Diss/SD	Contribution (%)	Cumulative (%)
Oligochaeta	**5.55**	**1.07**	**6.81**	**1.37**	**12.86**	**12.86**	**Nematoda**	**5.11**	**7.09**	**5.81**	**1.14**	**13.15**	**13.15**
Pygospio elegans	**6.08**	**4.57**	**5.42**	**1.14**	**10.22**	**23.08**	***Pygospio elegans***	**6.29**	**3.13**	**5.62**	**1.40**	**12.72**	**25.86**
***Capitella* Species Complex**	**3.70**	**3.71**	**4.93**	**1.21**	**9.30**	**32.39**	***Capitella* Species Complex**	**6.82**	**4.15**	**4.65**	**1.33**	**10.53**	**36.39**
Americorophium salmonis	**2.66**	**4.82**	**4.82**	**1.24**	**9.10**	**41.48**	***Americorophium salmonis***	**5.92**	**3.60**	**4.57**	**1.26**	**10.35**	**46.74**
Nematoda	**7.00**	**4.74**	**4.80**	**1.26**	**9.06**	**50.54**	**Harpacticoida**	**3.81**	**4.24**	**3.89**	**1.00**	**8.81**	**55.56**
Macoma balthica	**4.99**	**3.60**	**4.40**	**1.01**	**8.31**	**58.85**	**Oligochaeta**	**3.56**	**2.90**	**3.82**	**1.19**	**8.64**	**64.20**
Harpacticoida	**1.06**	**3.37**	**4.16**	**1.23**	**7.84**	**66.69**	***Nippoleucon hinumensis***	**1.81**	**2.74**	**3.54**	**1.02**	**8.01**	**72.21**
Nippoleucon hinumensis	2.79	1.76	4.02	0.95	7.59	74.28	*Eteone californica*	3.75	4.40	2.98	0.95	6.75	78.96
Eteone californica	**2.49**	**2.90**	**3.75**	**1.08**	**7.08**	**81.36**	***Macoma balthica***	**5.33**	**4.03**	**2.76**	**1.06**	**6.24**	**85.20**
Aricidea hartleyi	2.29	0.00	2.85	0.77	5.39	86.75	*Abarenicola pacifica*	1.15	0.55	1.68	0.63	3.81	89.02
Cumella vulgaris	1.67	1.13	2.69	0.86	5.08	91.83	*Paranemertes peregrina*	1.27	0.34	1.62	0.68	3.68	92.69
Chironomidae Larvae	0.33	0.99	1.66	0.55	3.14	94.97	*Cumella vulgaris*	0.15	0.76	1.03	0.43	2.32	95.02
Paranemertes peregrina	0.66	0.18	0.94	0.45	1.77	96.74	Ostracoda	0.00	0.64	0.82	0.39	1.85	96.87
Ostracoda	0.30	0.15	0.66	0.33	1.24	97.98	*Eogammarus confervicolus*	0.49	0.00	0.58	0.34	1.31	98.18

Diss/SD represents the ratio of the dissimilarity to the standard deviation. Values > 1, denoted in bold, represent groups that consistently contribute to the observed differences between location types. Taxa with Diss/SD < 1 did not consistently contribute to the observed differences between location types. Only groups that contributed ≥1% to the observed differences between locations are shown. DL: Dock Location. RL: Resort Location. NR: North Reference. SR: South Reference.

Table 4
SIMPER (Similarity Percentages) showing percent contribution (%) of each sediment variable collected at each quadrat (normalized) to the dissimilarity in sediment environment at Cassiar Cannery in Inverness Passage, during 2017.

May 30; DL vs (NR + SR)					May 30; RL vs (NR + SR)	
Average Squared Distance = 12.92					Average Squared Distance = 12.29	
Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist
Wood Cover (%)	3.48	0.74	26.94	26.94	Wood Cover (%)	2.74
Penetrability (mm)	2.34	0.81	18.08	45.02	Penetrability (mm)	2.17
aRPD (mm)	1.98	0.53	15.30	60.32	Water Content (%)	2.06
Water Content (%)	1.86	0.63	14.42	74.73	aRPD (mm)	1.97
Macrophyte Cover (%)	1.73	0.53	13.43	88.16	Particle Size	1.70
Particle Size	1.53	0.77	11.84	100	Macrophyte Cover (%)	1.66

May 30; DL vs (NR + SR)				May 30; DL vs RL				
Average Squared Distance = 12.92				Average Squared Distance = 12.73				
Variable	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)
Wood Cover (%)	0.57	22.28	22.28	Wood Cover (%)	2.40	0.71	18.87	18.87
Penetrability (mm)	0.79	17.67	39.94	Penetrability (mm)	2.25	0.74	17.69	36.56
aRPD (mm)	0.60	16.73	56.68	Macrophyte Cover (%)	2.15	0.43	16.93	53.48
Water Content (%)	0.46	16.04	72.71	Water Content (%)	2.07	0.72	16.24	69.72
Macrophyte Cover (%)	0.70	13.81	86.53	aRPD (mm)	1.95	0.77	15.31	85.03
Particle Size	0.58	13.47	100	Particle Size	1.91	0.71	14.97	100

June 21; DL vs (NR + SR)					June 21; RL vs (NR + SR)	
Average Squared Distance = 13.95					Average Squared Distance = 12.82	
Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist
Wood Cover (%)	**3.78**	**1.18**	**27.09**	**27.09**	aRPD (mm)	2.61
Penetrability (mm)	2.53	0.80	18.12	45.21	Penetrability (mm)	2.34
Water Content (%)	2.08	0.87	14.92	60.13	Wood Cover (%)	2.27
aRPD (mm)	2.03	0.77	14.56	74.69	Particle Size	2.06
Particle Size	1.81	0.49	12.94	87.63	Water Content (%)	1.87
Macrophyte Cover (%)	1.73	0.44	12.37	100	Macrophyte Cover (%)	1.67

June 21; DL vs (NR + SR)				June 21; DL vs RL				
Average Squared Distance = 13.95				Average Squared Distance = 14.38				
Variable	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)

(*continued on next page*)

Table 4 (*continued*)

June 21; DL vs (NR + SR)				June 21; DL vs RL				
Average Squared Distance = 13.95				Average Squared Distance = 14.38				
Variable	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)
Wood Cover (%)	0.79	20.35	20.35	**Wood Cover (%)**	**2.92**	**1.09**	**20.28**	**20.28**
Penetrability (mm)	0.76	18.28	38.62	Penetrability (mm)	2.72	0.9	18.92	39.2
Water Content (%)	0.76	17.71	56.33	aRPD (mm)	2.32	0.59	16.11	55.31
aRPD (mm)	0.63	16.05	72.39	Water Content (%)	2.27	0.87	15.76	71.07
Particle Size	0.70	14.59	86.97	Macrophyte Cover (%)	2.24	0.63	15.61	86.67
Macrophyte Cover (%)	0.53	13.03	100	Particle Size	1.92	0.68	13.33	100

July 20; DL vs (NR + SR)					July 20; RL vs (NR + SR)	
Average Squared Distance = 14.12					Average Squared Distance = 14.42	
Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist
Wood Cover (%)	3.62	0.90	25.65	25.65	Particle Size	3.12
Penetrability (mm)	2.36	0.97	16.68	42.34	Macrophyte Cover (%)	2.61
Particle Size	2.28	0.57	16.14	58.48	Water Content (%)	2.30
Water Content (%)	2.18	0.73	15.42	73.9	Wood Cover (%)	2.17
aRPD (mm)	2.04	0.49	14.43	88.33	Penetrability (mm)	2.17
Macrophyte Cover (%)	1.65	0.37	11.67	100	aRPD (mm)	2.05

July 20; DL vs (NR + SR)				July 20; DL vs RL				
Average Squared Distance = 14.12				Average Squared Distance = 13.05				
Variable	Sq.Dist/SD	Contribution (%)	Cumulative (%)	Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)
Wood Cover (%)	0.62	21.65	21.65	Wood Cover (%)	2.71	0.89	20.76	20.76
Penetrability (mm)	0.45	18.11	39.76	aRPD (mm)	2.28	0.53	17.48	38.24
Particle Size	0.78	15.98	55.74	Particle Size	2.15	0.62	16.49	54.73
Water Content (%)	0.43	15.02	70.76	Macrophyte Cover (%)	2.13	0.41	16.30	71.03
aRPD (mm)	0.59	15.02	85.78	Water Content (%)	1.89	0.79	14.49	85.52
Macrophyte Cover (%)	0.56	14.22	100	Penetrability (mm)	1.89	0.78	14.48	100

Particle size, aRPD, wood cover, and macrophyte cover were SQRT(X) transformed. Av. Sq. Dist: Average squared distance. Sq Dis/SD: Ratio of the average squared distance to the standard deviation. Values > 1, denoted in bold, represent variables that consistently contribute to the observed differences between location types. DL: Dock Location. RL: Resort Location. NR: North Reference. SR: South Reference.

Table 5
SIMPER (Similarity Percentages) showing percent contribution (%) of each nutrient variable (normalized) collected at each quadrat to the dissimilarity in nutrient availability between each location at Cassiar Cannery in Inverness Passage, during 2017. All variables were SQRT(X) transformed.

May 30 vs June 21				
Average Squared Distance = 4.96				
Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)
Chlorophyll *a* Concentration (mg/m^2)	3.13	0.56	63.1	63.10
Organic Matter Content (%)	1.83	0.76	36.9	100
May 30 vs July 20				
Average Squared Distance = 5.18				
Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)
Chlorophyll *a* Concentration (mg/m^2)	2.89	0.57	55.7	55.70
Organic Matter Content (%)	2.30	0.79	44.3	100
June 21 vs July 20				
Average Squared Distance = 2.28				
Variable	Av.Sq.Dist	Sq.Dist/SD	Contribution (%)	Cumulative (%)
Organic Matter Content (%)	2.10	0.81	91.74	91.74
Chlorophyll *a* Concentration (mg/m^2)	0.19	0.89	8.26	100

Av. Sq. Dist: Average squared distance. Sq Dis/SD: Ratio of the average squared distance to the standard deviation.

intensities compared to high light intensities (Muller et al., 1993; Raps et al., 1983). It is possible that these shade-acclimatized primary producers may be driving chlorophyll *a* productivity at DL, or tidal transport of diatoms to the substrate surface may be occurring under the dock. Regardless, future work should address how disturbance can influence species composition of photosynthetic organisms on intertidal mudflats. Additionally, as physical disruption to sediment can be detrimental to a variety of biotic parameters besides infaunal community composition (Dernie et al., 2003; Fonseca et al., 1982; Hansen and Skilleter, 1994) it was expected that the Resort Location would have reduced chlorophyll *a* concentration compared to the reference locations; however, this was not supported by the data.

While the physical disturbance at RL was not expected to alter organic matter content (Dernie et al., 2003), the dock and potential accumulation of wood fibres was expected to result in organic matter enrichment at DL, and the historic cannery may have led to organic matter enrichment compared to the reference locations. This was not observed, suggesting that if organic enrichment occurred, it has decreased over the past 25 years. Additionally, the average organic content in any location was not higher than non-organically enriched mudflats on the east coast of Canada (~2.2–4.5%; (Gerwing et al., 2015b) it was marginally higher than at other mudflats nearby, as well as within the disturbed Kitimat Estuary (1.81–3.97%; Campbell, Unpublished Data; Gerwing et al., 2018a). Future research should determine natural ranges of organic matter content at Northeast Pacific mudflats not experiencing anthropogenic nutrient inputs.

4.4. Passive reclamation

Passive reclamation can be highly effective in coastal and estuarine systems (Bayraktarov et al., 2016; Holl and Aide, 2011; Marquiegui and Aguirrezabalaga, 2009), while the associated costs of active reclamation can be extremely high (Bayraktarov et al., 2016; Holl and Aide, 2011). Additionally, there is no clear relationship between the cost of reclamation and the success of marine coastal reclamation efforts (Bayraktarov et al., 2016). At the Cassiar Cannery mudflat, quantifiable comparisons were not possible due to a lack of pre-disturbance data, but the cessation of historical activities would have allowed for passive reclamation. These findings suggest that passive reclamation was sufficient to return this intertidal mudflat to a relatively productive, functional and diverse ecosystem, therefore in some scenarios passive reclamation may be an effective reclamation tool without the burden of high operating costs (Holl and Aide, 2011). However, in this study passive reclamation did not restore the community to an entirely unstressed state, as evidenced by locally abundant populations of Capitellidae/Spionidae polychaetes and invasive cumaceans. Therefore, more time may be necessary for further progression towards an unstressed state, or a threshold may exist beyond which intertidal mudflats cannot be reclaimed through passive means. For instance, it is unlikely that an invasive species will passively die off once established.

The Cassiar Cannery mudflat would also have been impacted by chemical contaminants during its operation, and while this study did not quantify residual contaminants (e.g. copper or polycyclic aromatic hydrocarbons from the historical pulp mill and salmon cannery,) Sizmur et al. (In Press) showed no evidence of sediment contamination by potentially toxic elements (a naturally occurring element that can be toxic in high concentrations, e.g., arsenic, cadmium, cobalt, chromium, nickel, lead, and zinc) in the top 20 cm of the Cassiar Cannery mudflat. All potentially toxic elements studied at the Cassiar Cannery mudflat can be classified as unpolluted due to their low concentration (Muller, 1969). This result indicates that if contaminants were present, sediment inputs from the Skeena and Nass River have buried contaminated sediment as part of the passive reclamation process.

Passive reclamation therefore is an effective tool for intertidal mudflats; however, more research is required to see if thresholds exist to the efficacy of passive reclamation and whether these thresholds shift based on the level of disturbance to an estuarine system. Regardless, if thresholds do exist for passive reclamation but the goal is full reclamation, allowing for passive reclamation to the existing threshold before commencing active reclamation may be more cost-effective than a complete active reclamation scheme.

5. Conclusions

Overall the Cassiar Cannery mudflat appears to be relatively healthy and reasonably unstressed, and it appears that passive reclamation from historical disturbances has occurred at these locations. Therefore, passive restoration may be an appropriate reclamation technique in other soft-sediment or estuarine ecosystems degraded by industrial activities. However, within the mudflat, some patches ($1m^2$ quadrat) reveal the legacy of past disturbances in the form of patchy distributions of taxa which are known indicators of disturbance. Therefore, thresholds may exist to the efficacy of passive reclamation, and future research should address potential thresholds of reclamation. Regardless, allowing for passive reclamation of the soft-sediment ecosystem to a relatively unstressed state before commencing active reclamation may be successful without the high cost associated with a full active reclamation scheme.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seares.2019.101796.

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