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Depth to the apparent redox potential discontinuity (aRPD) as a parameter of interest in marine benthic habitat quality models

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ABSTRACT

The usefulness of the apparent redox potential discontinuity (aRPD) in assessments of marine benthic habitat quality was explored at two intertidal mudflats along the north Pacific coast of Canada. Two transects were established at each intertidal site, with three sediment biogeochemistry cores collected from each transect four times over the summer of 2016. Measurements of the sediment pore water dissolved oxygen (DO) content and redox (Eh) conditions were taken at the surface of the core (measured vertically), as well as at increasing depths (1 cm between readings) into the sediment (measured horizontally through predrilled holes in the biogeochemistry corer). While oxic, anoxic, oxidized, and reduced sediment pore water was observed above and below the aRPD, in general, sediment above the aRPD had higher DO content, and higher Eh values than sediment below the aRPD. Therefore, the aRPD depth can be used as a relative indicator of sediment pore water DO and Eh conditions: sediment with a deeper aRPD depth has more available DO, and the pore water has higher Eh values (more oxidized or less reduced) than sediment with a shallower aRPD depth. As such, the aRPD depth is a useful parameter to include in models that assess the quality of marine benthic habitats.

1. Introduction

In order to categorize and understand the natural world, ecologists have long been driven to find ways to quantify the quality, or health, of various habitats (Diaz et al., 2004; Johnson, 2007). As climate change radically alters global ecosystems (Houghton et al., 2001), the need to assess habitat quality is becoming increasingly important. This change is readily apparent in the world's oceans, as increasing global temperatures alter oceanic chemistry, increase water temperature, and decrease dissolved oxygen (DO) content (Diaz & Rosenberg, 2008; Houghton et al., 2001; Stachowicz et al., 2002).

Often included in marine habitat quality models, especially models examining benthic sediment (Birchenough et al., 2012; Diaz & Rosenberg, 1995; Diaz et al., 2004; Diaz & Trefry, 2006), are measurements of sediment DO content and redox potential (Eh). Warm water holds less DO than cold water (Kristensen, 2000), therefore, decreasing DO content due to global warming may represent a substantial stressor for aerobic metazoans (Diaz & Rosenberg, 2008; Ferguson et al., 2013). In fact hypoxia (low oxygen conditions, exact values vary by species; Vaquer-Sunyer & Duarte, 2008) and anoxia (DO $\leq$ 0.0 mg/L; Tyson & Pearson, 1991) have already resulted in vast dead zones in over 400 marine systems (Diaz & Rosenberg, 2008). Therefore, hypoxia represents a major threat facing many marine systems (Halpern et al., 2007). More specifically, DO may already represent a limiting resource in benthic marine habitats (Ferguson et al., 2013). Hypoxia/anoxia has been observed to result in infaunal mortality (Altieri & Witman, 2006; Nilsson & Rosenberg, 2000), migration (Sturdivant et al., 2012), and altered bioturbation activity (Nilsson & Rosenberg, 2000; Rosenberg et al., 2001; Sturdivant et al., 2012). Given the dramatic consequences of hypoxia and anoxia (Diaz & Rosenberg, 2008; Nilsson & Rosenberg, 2000), it is no surprise that DO content is often included in assessments of benthic habitat quality (Diaz et al., 2004; Nilsson & Rosenberg, 2000).

Redox measurements quantify the tendency of sediment/water to donate or accept electrons (Pearson & Rosenberg, 1978;

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Rosenberg et al., 2001). Positive Eh values indicate oxidized sediment, while negative Eh values indicate reduced sediment. Redox conditions are often included in assessments of benthic habitat quality (Birchenough et al., 2012; Diaz et al., 2004), however, the parameter of interest often is depth to the redox potential discontinuity (RPD) in the sediment. The RPD marks the transition from oxidized to reduced sediment conditions (Fenchel & Riedl, 1970; Lyle, 1983; Sturdivant et al., 2012). A shallower RPD, or strongly reduced sediment, often is associated with disturbances such as organic enrichment or hypoxia/anoxia (Diaz & Rosenberg, 1995; Diaz & Trefry, 2006; Mazzola et al., 2000; Pearson & Rosenberg, 1978; Rosenberg et al., 2001).

Measurement of DO or redox conditions in benthic sediment requires extracting a sediment core, and inserting DO/redox electrodes into the sediment. Readings must be taken at increasing sediment depths (by inserting electrodes horizontally into the sediment core) to determine the depth to the RPD, as well as oxygen penetration into the sediment. The stabilization time of Eh and DO readings can vary from 30 s to 45 min (Gerwing et al., 2013). As a single profile can include 10–20 readings, and multiple profiles are required to characterize a study area, the time required to collect these data often is prohibitive, especially in intertidal systems (Gerwing et al., 2013, 2015b). Fortunately, a method exists to quantify RPD depth visually, and when redox measurements (Eh) are not considered simultaneously, the visually assessed RPD is termed the apparent redox potential discontinuity, or aRPD (Birchenough et al., 2012; Solan et al., 2004; Teal et al., 2009). The aRPD demarks a color transition in the sediment, from brownish/red sediment, to sediment that is grey/green, or black (Munari et al., 2003; Sturdivant et al., 2012; Teal et al., 2009).

This color change is a product of redox reactions, and how these reactions vary in the presence or absence of oxygen. In the absence of oxygen, iron (Fe) and sulphur (S) are reduced by microbial activity, turning the sediment grey/green or black (Bull & Taillefert, 2001; Bull & Williamson, 2001; Lyle, 1983; Valdemarsen et al., 2009). Microbes responsible for this color change are usually also involved in decomposition of organic matter (Kristensen, 2000; Teal et al., 2010; Valdemarsen et al., 2009). Within sediment pore water, oxygen is the most energetically favored electron acceptor (Kristensen, 2000), as well as the most reactive (Woodin et al., 2010). As such, ions that induce sediment color change cannot persist for long in the presence of oxygen (Hargrave, 1972; Revsbech et al., 1980). Therefore, the aRPD is located where the sediment changes from reddish-brown to grey/green or black (Munari et al., 2003; Sturdivant et al., 2012; Teal et al., 2009). The aRPD often is used as a measure of oxygen penetration into the sediment (Diaz & Trefry, 2006; Rosenberg et al., 2001; Solan & Kennedy, 2002), and other studies have reported that sediment below the aRPD, black sediment, often exhibits lower Eh values, indicating reduced sediment (Diaz & Trefry, 2006; Pearson & Stanley, 1979). Put simply, sediment with a grey/green or black color is assumed to be in a reduced state, with little to no oxygen present in the pore water. Sediment with a brown or red color is assumed to be in an oxidized state with oxygen present in the pore water (Gerwing et al., 2015).

Despite being frequently used in benthic habitat quality models (Birchenough et al., 2012; Gerwing et al., 2017; Rosenberg et al., 2001; Teal et al., 2010), the appropriateness of using the aRPD depth as a measure of habitat quality is not clear, as aRPD depth is impacted by more than just DO and redox conditions. As discussed in Gerwing et al. (2015), the presence and concentration of color-inducing ions, decomposition activity of sediment microbes (Hunting & Kampfraath, 2013; Kristensen, 2000; Teal et al., 2010), sediment organic carbon content, and chlorophyll *a* concentration will influence aRPD depth (Diaz & Trefry, 2006; Kristensen, 2000; Rosenberg et al., 2001; Teal et al., 2010). Bioturbation and irrigation of faunal burrows (Solan & Kennedy, 2002; Sturdivant et al., 2012) will also influence aRPD depth by introducing oxygen-rich water deep into the sediment, creating a three dimensional mosaic of oxygen conditions (Kristensen, 2000; Solan & Kennedy, 2002). Even the usefulness of the color change that characterizes the aRPD is unclear. Oxidization and reduction of ferric sulfides, the primary reaction responsible for sediment color change, does not occur instantly (Grenthe et al., 1992; Lyle, 1983; Valdemarsen et al., 2010). Sediment color change may therefore lag behind sediment DO and redox conditions (Lyle, 1983; Teal et al., 2010). Finally, studies conducted subtidally have found a good correlation between RPD and aRPD depth (Diaz & Trefry, 2006; Rosenberg et al., 2001), while one intertidal study did not (Gerwing et al., 2013). As such, the usefulness of including aRPD depth in habitat quality models remains unclear, especially in intertidal systems.

In an attempt to determine if the aRPD depth is an important parameter to include in habitat quality models, Gerwing et al. (2015) measured sediment pore water DO content above and below the aRPD on intertidal mudflats in the Bay of Fundy, along the Atlantic coast of Canada. Gerwing et al. (2015) observed that more DO was present above the aRPD than below; therefore, aRPD depth could be used as a relative measure of sediment pore water DO content. Sediment with a deeper aRPD has more available DO, while sediment with a shallower aRPD has less available DO (Gerwing et al., 2015). Unfortunately that study was only done at one intertidal mudflat, on a single day, and did not examine redox values (Gerwing et al., 2015). Given the limited spatiotemporal scale of Gerwing et al. (2015b)'s study, and their failure to examine redox conditions, more work is required to determine if aRPD depth is a useful parameter to include in habitat quality models.

As such, the goals of this study are twofold: First, to repeatedly assess if depth to the aRPD is a useful relative indicator of sediment pore water DO content on two intertidal mudflats along the Pacific coast of Canada. Second, to determine if aRPD depth, a visual measure of sediment color, is an effective measure of sediment redox conditions. Determining aRPD depth's utility in estimating sediment DO and redox conditions will help elucidate the usefulness of this parameter in models assessing habitat quality.

2. Materials and methods

2.1. Study sites

This study was done on two soft-sediment, intertidal mudflats (Cassiar Cannery [CC] and Wolfe Cove [WC]) along the north coast of British Columbia, Canada (Fig. 1). The infaunal communities in this area are dominated by Cumacea, bivalves, amphipods, oligochaetes, and polychaetes (Gerwing, 2016). Sediment at both sites was dominated by fine silts, with small amounts of fine-grained sand also present (McLaren, 2016). This coastal ecosystem is strongly estuarine, exhibiting variable salinities due to the input of freshwater from the nearby Skeena river (Ages, 1979; McLaren, 2016; Trites, 1956). Due to strong semidiurnal tides (tidal amplitudes can reach 7.5 m), and the interaction of tides with river currents, strong eddies and currents can form in passages and channels (Ages, 1979; McLaren, 2016; Trites, 1956). Detailed information on current strengths, sediment deposition, and glacial history of the study area can be found in McLaren (2016).

2.2. Data collection

Each site was sampled four times over the summer of 2016 (Sampling Round: Cassiar Cannery: June 24th, July 3rd, July 6th, and July 23rd; Wolfe Cove: June 25th, July 4th, July 7th, and July 24th). At each site, two transects were randomly established 10 m

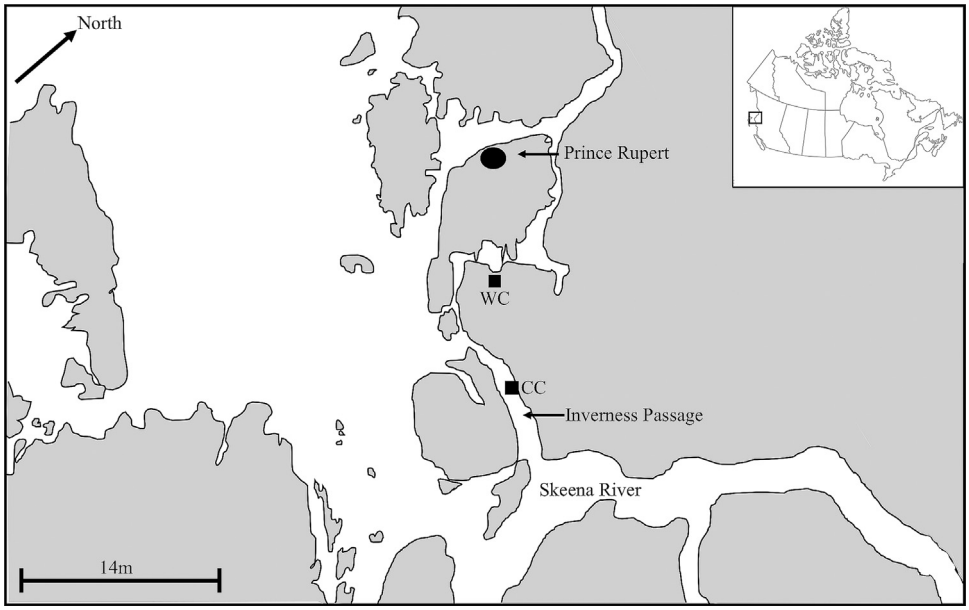

Fig. 1. Intertidal study sites, Cassiar Cannery (CC; 54.178092°N, −130.176924°W) and Wolfe Cove (WC; 54.242119°N, −130.273394°W) along the north coast of British Columbia.

from each other, stretching from the start of the mudflat (transition from saltmarsh to mudflat at Cassiar Cannery, and the transition from rocky intertidal to mudflat at Wolfe Cove) to the low-water line. At both sites this distance was ~60 m. Transects were divided into three zones based upon distance from the start of the mudflat: near, middle, and far (Gerwing et al., 2016). Within each zone, one random location was selected along the transect using a random number generator.

At each location, a sediment biogeochemistry core was collected using a modified version of the corer described in Gerwing et al. (2015). The corer was 20 cm long, had a diameter of 12 cm, and along each side were predrilled holes (2 cm diameter, and 1 cm between holes). Holes present on both sides of the corer allowed Eh and DO readings to be collected simultaneously. Spacing the predrilled holes 1 cm apart enabled redox and DO measurements to be taken at increasing sediment depths, thus, allowing redox and DO profiles to be elucidated. As described in Gerwing et al. (2015), at each sampling location, the corer was inserted as far as possible into the sediment. The sediment core was then removed, and DO and redox readings were immediately taken. Electrodes were inserted ~1–3 mm into the top of the sediment (vertically) to measure DO concentration (mg/L) and Eh conditions (millivolts) at the surface (depth = 0 cm), and then horizontally into the sediment core (~1 cm) through the pre-drilled holes in the corer (Gerwing et al., 2015). DO was quantified with the SevenGO(Duo) pro/OptiOx Meter and InLab OptiOX DO electrode made by Mettler Toledo (Gerwing et al., 2015). Redox conditions were measured using a silver/platinum electrode (Orion Combination Metal Electrodes. 9778BNWP. ThermoFisher Scientific, Ottawa, Ontario, Canada) and a field redox meter (EcoScan pH6. EC-PH6/02 K. ThermoFisher Scientific), as described in Gerwing et al. (2013). Redox and DO readings at each depth interval were allowed to stabilize before being recorded (Whitfield, 1969), and electrodes were cleaned between readings and sampling rounds (Whitfield, 1969; Wildish et al., 2004). Redox values were corrected to the standard hydrogen potential (Hargrave, 1972; Hargrave et al., 1997; Whitfield, 1969), and Eh and DO electrodes were calibrated before each sampling round. Temperature (for Eh and DO corrections) was measured using a digital meat thermometer at each depth interval. Redox, DO content, and salinity (using a refractometer) also were measured in the water directly above the sediment (~1 cm) from each site at high and low tide. Finally, depth to the aRPD was measured, to the nearest millimetre, from the void left in the sediment following extraction of the biogeochemistry core as described in Gerwing et al. (2013).

2.3. Statistical analysis

All statistical analyses were done using R-studio. Generalized linear regression mixed models were used to evaluate the effect of position of a reading relative to the aRPD (categorical: above or below), depth of a reading into the sediment (Depth; continuous variable), distance of the profile from shore (DFS; continuous variable), sampling round (categorical; four levels, Sampling Round 1: Cassiar Cannery: June 24, 2016; Wolfe Cove: June 25, 2016. Sampling Round 2: Cassiar Cannery: July 3, 2016; Wolfe Cove: July 4, 2016. Sampling Round 3: Cassiar Cannery: July 6, 2016; Wolfe Cove: July 7, 2016. Sampling Round 4: Cassiar Cannery: July 23, 2016; Wolfe Cove: July 24, 2016), site (Wolfe Cove or Cassiar Cannery; categorical variable), and transect nested within site (transect(site)) on DO and Eh conditions in sediment pore water. Categorical variables were contrasted using deviation coding as suggested in Menard (2002). All variables were fixed effects, except transect, which was a random effect included in every model to control for multiple measurements within a site (Gerwing et al., 2012).

DO and Eh conditions were analyzed separately, and for each response variable seven models, selected *a priori*, were evaluated using the Information Theoretic Model Selection Approach (Burnham & Anderson, 2001; Burnham et al., 2011). This approach utilizes multiple lines of evidence to select the "top" performing or "best" model from amongst a series of candidate models designed *a priori*. All possible permutations of aRPD, DFS, and depth were evaluated; however, in all models the variables sampling round, site, and transect were included to adequately represent the spatiotemporal structure of the data. Candidate top-ranked model (s) were selected by calculating Δ AIC_c values (where AIC is the Akaike Information Criterion), and models with a Δ $AIC_c < 2$ were considered to be equivalent (Burnham & Anderson, 2002; Burnham et al., 2011). When multiple models were considered equivalent, the most parsimonious model was selected as the top ranking model (Richards, 2008; Richards et al., 2011). The

Table 1
Dissolved oxygen concentration (mg/L), salinity (PSU), and redox potential (Eh; millivolts) of the water directly above (~1 cm) the sediment surface at two intertidal mudflats along the north coast of British Columbia. Data were collected at high and low tide. See Fig. 1 for full site names.

Date	Site	Dissolved oxygen concentration		Salinity		Redox potential	
		High tide	Low tide	High tide	Low tide	High tide	Low tide
June 25 2016	WC	10.61	11.04	15	19	128	135
July 4 2016	WC	10.45	9.88	21	20	118	100
July 7 2016	WC	11.55	11.18	19	19	90	121
July 24 2016	WC	10.98	11.28	20	20	114	90
June 24 2016	CC	11.87	10.11	10	6	127	115
July 3 2016	CC	10.11	10.58	10	8	140	136
July 6 2016	CC	11.30	10.27	11	8	92	121
July 23 2016	CC	9.77	9.70	10	4	144	116

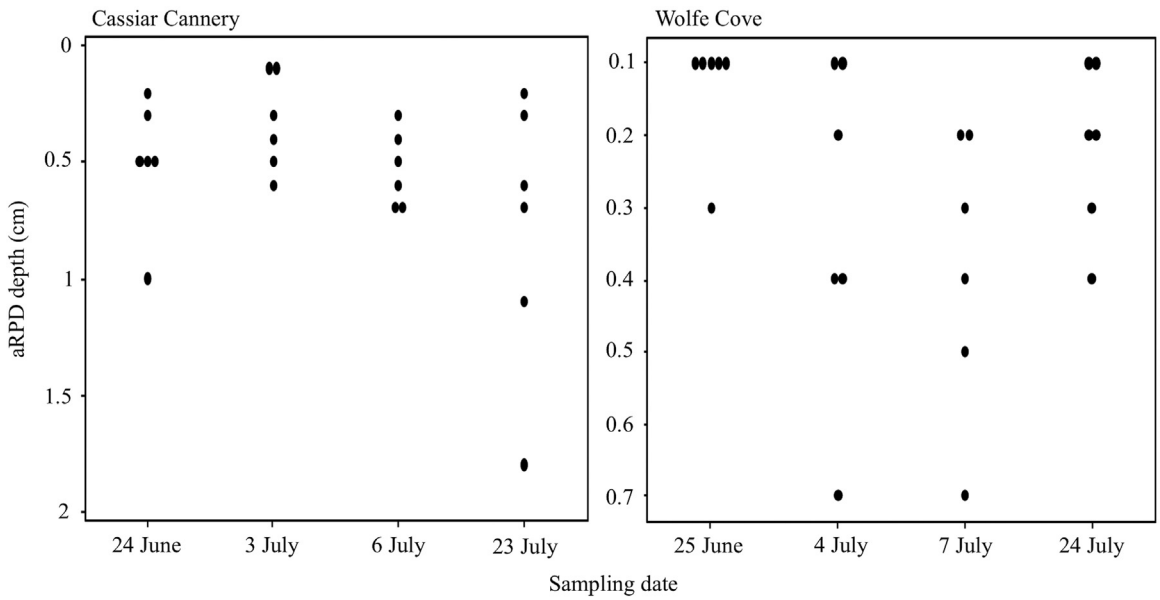

Fig. 2. Depth to the apparent redox potential discontinuity (aRPD) measured at two intertidal study sites along the north coast of British Columbia during the summer of 2016. "0" represents the surface of the intertidal sediment, followed by increasing depth into the sediment. n = six points at each site/sampling round iteration.

Table 2
Summary table of generalized linear mixed effects models assessing if redox conditions (Eh) or dissolved oxygen concentration (DO) varied above or below the apparent redox potential discontinuity (aRPD), at stratified random distances from the shore (DFS), along two transects (random factor nested within site), at two intertidal mudflat study sites along the north coast of British Columbia in 2016. k is the number of terms in the model, plus the constant. R^2 is the proportion of the DO or Eh variation each model accounted for. SE is the standard error and MAE represents the mean absolute error. The ratio of the mean absolute DO concentration (0.36 mg/L) or Eh conditions (139.70 mv) over the MAE indicates the predictive ability of the model. Values greater than 1 indicate a predictive model, while values below 1 indicate non predictive models.

Rank	Model	k	ΔAIC_C	AIC_C	AIC_C w	R^2	MAE	Mean [Eh]/MAE
Eh								
1	aRPD + DFS + Depth + Site + Transect(Site) + Sampling Round	15	0	4867.97	1	0.66	49.19	2.84
2	aRPD + DFS + Site + Transect(Site) + Sampling Round	14	52.47	4920.44	0	0.62	52.31	2.67
3	aRPD + Depth + Site + Transect(Site) + Sampling Round	14	66.14	4934.11	0	0.60	53.52	2.61
3	aRPD + Site + Transect(Site) + Sampling Round	13	66.14	4934.11	0	0.60	53.52	2.61
4	DFS + Depth + Site + Transect(Site) + Sampling Round	13	164.06	5032.03	0	0.51	53.52	2.61
5	Depth + Site + Transect(Site) + Sampling Round	12	174.77	5042.74	0	0.50	58.33	2.39
6	DFS + Site + Transect(Site) + Sampling Round	12	308.28	5176.25	0	0.32	65.68	2.13
DO								
1	aRPD + Site + Transect(Site) + Sampling Round	13	0	1399.93	0.98	0.41	0.44	0.83
2	aRPD + Depth + Site + Transect(Site) + Sampling Round	14	8.27	1408.20	0.02	0.41	0.44	0.83
3	aRPD + DFS + Depth + Site + Transect(Site) + Sampling Round	15	20.08	1420.01	0	0.41	0.44	0.83
4	aRPD + DFS + Site + Transect(Site) + Sampling Round	14	11.81	1411.74	0	0.41	0.44	0.83
5	Depth + Site + Transect(Site) + Sampling Round	12	191.00	1590.93	0	0.10	0.69	0.52
6	DFS + Depth + Site + Transect(Site) + Sampling Round	13	202.43	1602.36	0	0.10	0.69	0.52
7	DFS + Site + Transect(Site) + Sampling Round	12	234.76	1634.69	0	0.01	0.64	0.57

Table 3
Details of the top-ranked models (see Table 2) for assessing if redox conditions (Eh) or dissolved oxygen concentration (DO) varied above or below the apparent redox potential discontinuity (aRPD) at two intertidal mudflat study sites along the north coast of British Columbia in 2016. SE is the standard error, and DFS is distance from shore. Sampling Round 1: Cassiar Cannery: June 24th; Wolfe Cove: June 25th. Sampling Round 2: Cassiar Cannery: July 3rd; Wolfe Cove: July 4th. Sampling Round 3: Cassiar Cannery: July 6th; Wolfe Cove: July 7th. Sampling Round 4: Cassiar Cannery: July 23rd; Wolfe Cove: July 24th.

Parameter	Coefficient	SE	95% CI	T-value	P-value
Eh					
aRPD: above	17.70	12.97	−2.33 to 37.49	1.37	0.17
aRPD: below	−126.36	11.18	−143.27 to −109.62	−11.30	< 0.001
Site: Cassiar Cannery	−229.92	10.36	−245.53 to −214.72	−22.20	< 0.001
Site: Wolfe Cove	−126.36	11.18	−143.27 to −109.62	−11.30	< 0.001
Sampling Round 1	−229.92	10.36	−245.53 to −214.72	−22.20	< 0.001
Sampling Round 2	−223.93	10.89	−240.40 to −207.74	−20.55	< 0.001
Sampling Round 3	−207.36	10.17	−222.54 to −192.39	−20.38	< 0.001
Sampling Round 4	−156.65	11.22	−173.73 to −139.92	−13.96	< 0.001
DFS	0.69	0.15	0.45 to 0.94	4.60	< 0.001
Depth	−7.26	0.97	−8.83 to −5.66	−7.49	< 0.001
DO					
aRPD: above	3.02	0.21	2.70 to 3.34	14.28	< 0.001
aRPD: below	0.07	0.15	−0.15 to 0.28	0.45	0.65
Site: Cassiar Cannery	0.02	0.16	−0.21 to 0.24	0.10	0.92
Site: Wolfe Cove	−0.12	0.16	−0.35 to 0.12	−0.71	0.48
Sampling Round 1	0.02	0.16	−0.21 to 0.24	0.10	0.92
Sampling Round 2	0.27	0.16	0.05 to 0.50	1.75	0.08
Sampling Round 3	−0.01	0.15	−0.23 to 0.21	−0.04	0.97
Sampling Round 4	0.07	0.15	−0.15 to 0.28	0.45	0.65

probability of each model being the "best" model of the candidate set, AIC_c *w*, also was calculated (Burnham & Anderson, 2001; Lukacs et al., 2007; Richards, 2005). Finally, the predictive ability of each model was determined by calculating the ratio of the mean DO content or Eh conditions to the mean absolute error (MAE). Values greater than 1 indicate a predictive model, while values below 1 indicate non-predictive models (Willmott & Matsuura, 2005). Models were constructed in R-studio using the *glmer* function within the lme4 package (Bates et al., 2015). The mean absolute error and the coefficient of determination (R^2) of each model were then determined using the *Metrics* and *MuMI* packages, respectively (Hamner, 2012; Mazerolle, 2016). The AIC_c of each model was determined using the *AICC* function within the *AICcmodavg* package (Mazerolle, 2016).

3. Results

While the water above the sediment surface (Table 1) exhibited variable salinities (between sites, dates, and tides), the water was highly oxidized (positive Eh values) and contained ample DO. The aRPD depth varied over space and time (Fig. 2 and Tables 2 and 3), and redox as well as DO conditions were variable within the sediment (Fig. 3). Oxidized and reduced, as well as oxic and anoxic sediment pore water was observed above and below the aRPD. In general, however, higher Eh and DO values were observed above the aRPD than below (Fig. 3, Tables 2 and 3).

With regards to Eh conditions, the top-ranked model (Tables 2 and 3) included all the parameters of interest (above or below the aRPD, DFS, and depth), was highly predictive (Mean [Eh]/MAE: 2.84), and explained a high proportion of the variation in Eh readings (R^2: 0.66). The top ranked DO model did not include DFS or depth, only if a measurement was above or below the aRPD. None of the DO models were predictive, as their Mean [DO]/MAE ratios were all below 1, and DO models explained a small portion (R^2: 0.01–0.41) of the variation in DO conditions (Tables 2 and 3).

4. Discussion

To elucidate if the aRPD depth is a useful parameter to include in assessments of marine benthic habitat quality, it was examined if the aRPD depth was a good indicator of sediment pore water redox (Eh) and DO conditions at two intertidal mudflats along the north coast of British Columbia, Canada. While reduced, oxidized, oxic, and anoxic sediment pore water was observed above and below the aRPD, in general more DO and higher Eh values were observed above the aRPD than below (Fig. 3, Tables 2 and 3). Higher DO (Diaz & Trefry, 2006; Rosenberg et al., 2001; Solan & Kennedy, 2002) and Eh (Diaz & Trefry, 2006; Gerwing et al., 2013; Pearson & Stanley, 1979) values above the aRPD have been observed before in intertidal, subtidal, and deep sea sediments. Further, the findings of this study build upon the conclusions of Gerwing et al. (2015). In the Bay of Fundy, Gerwing et al. (2015) observed higher DO content in sediment pore water above the aRPD than below. Gerwing et al. (2015) postulated that aRPD depth may be a good relative indicator of sediment pore water DO content; however, this study was done over a limited spatiotemporal scale, and did not examine redox conditions. The results of the current study build upon this premise by examining sediment pore water DO and Eh conditions at a broader spatiotemporal scale (two mudflats, sampled four times over the summer of 2016). The current findings support the observations of Gerwing et al. (2015), as the current study also observed more DO above the aRPD than below. Moreover, the current study adds to the findings of Gerwing et al. (2015), as the current study also found higher Eh values above the aRPD than below. Therefore, the aRPD depth can be used as a relative indicator not only of sediment pore water DO content, but Eh conditions as well. Sediment with a deeper aRPD depth has more available DO, and the pore water has higher Eh values (more oxidized or less reduced) than sediment with a shallower aRPD depth. As such, the aRPD depth is a useful parameter to include in models that assess the quality of marine benthic habitats, especially for aerobic metazoans.

It is important to note that it is not suggested that the aRPD depth is an analytical method to evaluate sediment pore water DO or Eh conditions. Nor is it suggested that black sediment indicates anoxia, or that aRPD depth is indicative of RPD depth; however, interested readers can refer to Diaz and Trefry (2006), Gerwing et al. (2013) and Rosenberg et al. (2001) for such comparisons. Quantification of actual Eh and DO conditions would require Eh and DO electrodes/meters, not an assessment of sediment color. As previously discussed, aRPD depth can only be used as a relative

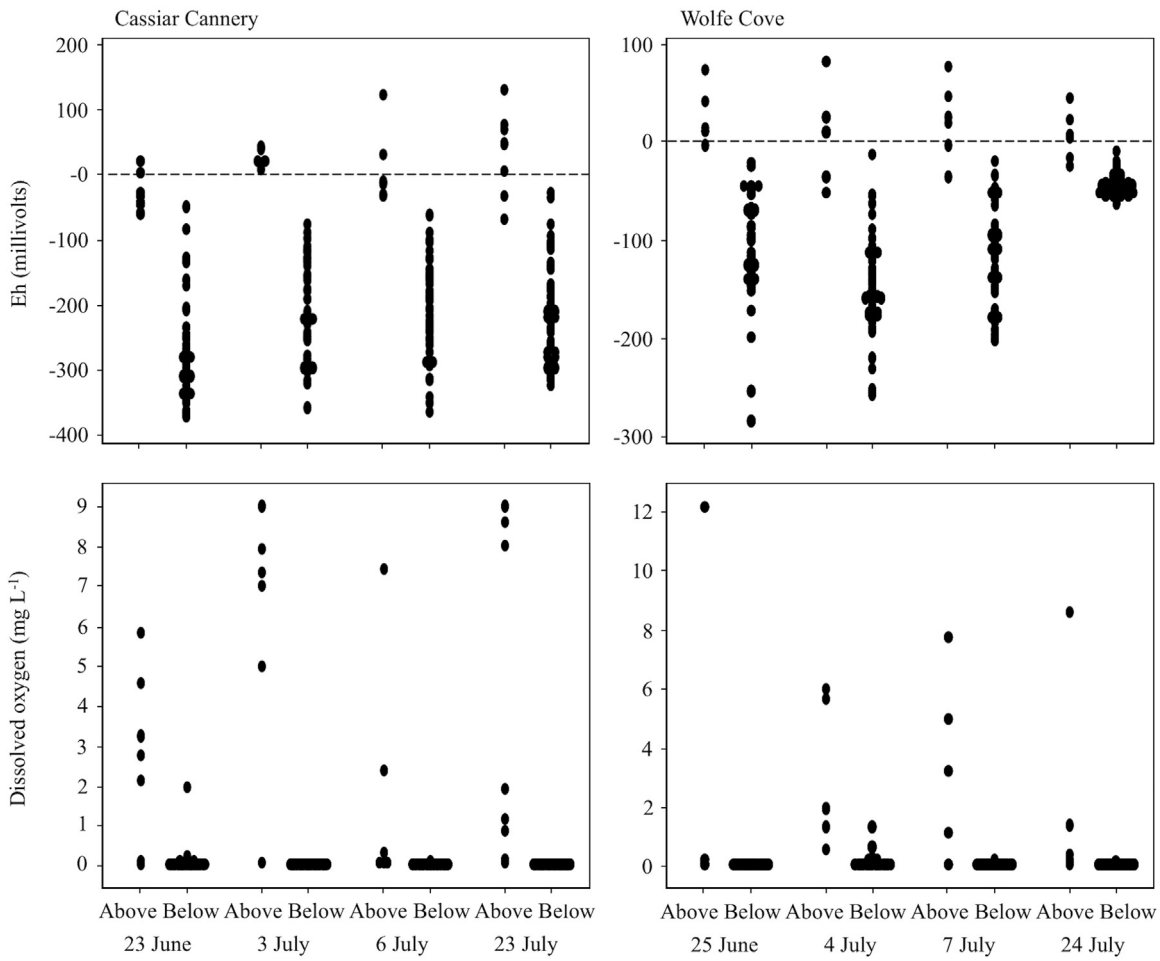

Fig. 3. Sediment redox potential (Eh) and pore water dissolved oxygen concentration measured above and below the apparent redox potential discontinuity (aRPD) at two intertidal study sites along the north coast of British Columbia during summer 2016 (Above: n=6–9; Below –=36–72).

measure of sediment pore water DO and Eh conditions; sediment with a deeper aRPD has more available DO and higher Eh values than sediment with a shallower aRPD.

Despite this limitation, the aRPD depth is a useful parameter to include in models that assess the quality of marine benthic habitats. For instance, see Clare et al. (2016) who included the aRPD depth in their assessment of ecosystem functioning in the Mersey Estuary (UK). Given that infaunal mortality (Altieri & Witman, 2006; Nilsson & Rosenberg, 2000), migration (Sturdivant et al., 2012), and altered bioturbation activity (Nilsson & Rosenberg, 2000; Rosenberg et al., 2001; Sturdivant et al., 2012) are associated with hypoxic/anoxic conditions, as well as that reduced sediment is often associated with disturbances such as organic enrichment, or hypoxia/anoxia (Diaz & Rosenberg, 1995; Diaz & Trefry, 2006; Mazzola et al., 2000; Pearson & Rosenberg, 1978; Rosenberg et al., 2001), aRPD depth is a useful, if relative, parameter to include in assessments of benthic habitat quality.

Further, it is posited that the non-instantaneous nature of the color change associated with the aRPD depth strengthens the argument to utilize the aRPD depth as a measure of habitat quality. The primary reactions responsible for sediment color change are the oxidization and reduction of ferric sulfides, and these reactions do not occur instantly (Grenthe et al., 1992; Lyle, 1983; Valdemarsen et al., 2010). Therefore, sediment color will lag behind the actual DO and Eh conditions (Lyle, 1983; Teal et al., 2010). Furthermore, the numerous biological (bioturbation, activity of sediment microbes, etc.) and abiotic (sediment particle size, porosity, etc.) factors that influence the aRPD depth, result in DO and Eh conditions varying at spatiotemporal scales as fine as seconds or millimetres (Jovanovic et al., 2014; Pischedda et al., 2012; Wenzhofer & Glud, 2004). But as sediment color change lags behind instantaneous Eh and DO conditions, these biotic and abiotic factors likely do not cause aRPD depth to vary at similarly fine spatiotemporal scales. As such, the observed aRPD depth is likely an integrated, long-term average of all the processes (biotic and abiotic) influencing aRPD depth at that location. Quantification of Eh or DO values using electrodes/meters will capture fine-grained variation in DO and Eh conditions, however, the number of profiles required to elucidate Eh and DO at broad spatiotemporal scales is prohibitive (Gerwing et al., 2013; Gerwing et al., 2015). The aRPD depth, on the other hand, can easily be measured across broad spatiotemporal scales, and as the data represent an integrated, long-term average of Eh and DO conditions in that area, the aRPD depth is a good parameter to include in models assessing benthic habitat quality.

Finally, before the aRPD depth is utilized as a relative measure of Eh and DO conditions in other habitats, the relations reported here must be confirmed in individual study areas. While similar trends in DO content (Diaz & Trefry, 2006; Gerwing et al., 2015; Rosenberg et al., 2001; Solan & Kennedy, 2002) and Eh conditions (Diaz & Trefry, 2006; Pearson & Stanley, 1979) have been reported from intertidal, subtidal, and deep sea sediments, the aRPD depth may not be a useful parameter in all benthic habitats (Gerwing et al., 2015). For instance, the depth to the aRPD will not be as useful in sandy sediment, or in sediment with low Fe content, as the

aRPD will be less visible than in Fe-rich sediment composed of silt/clay (TG Gerwing Personal Observation).

5. Conclusions

Despite the limitations discussed in this paper, the aRPD depth has been shown to be a good relative indicator of sediment pore water Eh conditions and DO content. Sediment with a deeper aRPD depth has more available DO, and the pore water has higher Eh values (more oxidized or less reduced) than sediment with a shallower aRPD depth. As such, the aRPD depth is an effective measure to include in assessments of benthic habitat quality, especially for aerobic metazoans. Such measures, capable of quickly assessing habitat quality across broad spatiotemporal scales, will become increasingly useful as climate change radically alters marine ecosystems.

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