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Establishing biologically relevant sediment organic matter thresholds for estuaries and embayments of the Southern California Bight, USA

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ABSTRACT

Estuaries, lagoons, and embayments are key components of the coastal ecosystem and they are pervasively exposed to a variety of stressors – the most common of which is eutrophication. In shallow water coastal systems, eutrophication typically manifests as shifts in sediment oxygen horizons and accumulation of toxic reduced compounds in the porewater, which have direct, negative effects on the benthic fauna that live in these sediments. To catalog, prevent, and remediate these stressors, the coastal zone management community has expressed a need to identify targets for biostimulatory compounds and products in the environment that are protective of biological integrity of coastal waters. In response to this need, the present study identified and validated a series of sediment total organic carbon (TOC) and total nitrogen (TN) concentrations associated with changes in macrobenthic community composition across the estuaries and embayments of the Southern California Bight (SCB). Using data from a regional monitoring program, benthic community condition, quantified using the M-AMBI condition assessment index, was modelled as a function of TOC or TN concentration using logistic regression. Then, we evaluated eutrophication thresholds at concentrations corresponding to several relative probabilities (from 0.6 to 0.8), reflecting a range of policy makers' potential tolerance for risk of failing to meet biointegrity goals. Organic matter thresholds were extracted from the regressions that were predictive of healthy macrobenthic community condition at a 0.8 probability (1.23 mg g^{-1} TN, 15.51 mg g^{-1} TOC), 0.7 probability (2.58 mg g^{-1} TN, 22.9 mg g^{-1} TOC), or 0.6 probability (3.68 mg g^{-1} TN, 28.96 mg g^{-1} TOC) – as an illustration of how these types of stressor response models could be used to set targets for management of these ecosystems. These thresholds were subsequently validated by applying them to data held back from the model creation and by comparing them to taxon-specific inflection points identified from TITAN changepoint analysis of the macrobenthic/TOC/TN calibration data. The different TOC and TN thresholds correctly classified between 67 and 86% of the validation samples, with most of the misclassifications being instances of low organic matter concentration but poor community condition (i.e., false positives). The TOC thresholds identified from our Southern California dataset fell within a similar range (10–35 mg g^{-1}) that has been linked to benthic community impacts from a variety of coastal ocean sites across the Northern Hemisphere. The consistency in thresholds across multiple habitats and different types of biota is suggestive of a general, quantitative threshold for organic matter accumulation in near shore sediment habitats and could be useful for informing the management of coastal ecosystems and setting targets biostimulatory stressors in these systems.

1. Introduction

Estuaries, lagoons, and embayments are some of the most ecologically and societally important, yet pervasively disturbed, aquatic habitats. While a variety of different stressors impact these systems, the most common present-day threat stems from eutrophication (National Research Council, 2000, Howarth et al., 2002), the accumulation of excessive organic matter in an ecosystem (Nixon, 1995, 2009, Smith and Schindler, 2009). Understanding the effects of eutrophication on biological resources of the coastal zone is one of the most pressing challenges facing environmental managers and regulators responsible for these waters and the watersheds they drain. While anthropogenic nutrient loading is one of the major factors driving eutrophication, other environmental drivers such as hydromodification, habitat alteration, organic matter dumping, etc., can exacerbate this problem. For this reason, managing systems towards specific nutrient loads independent

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of biotic responses has a mixed record of success (e.g., Smith et al., 1999, Stow and Borsuk, 2003). Biologically relevant thresholds are needed to assess organic matter accumulation and its impacts on the flora and fauna of a system to provide a more modern, ecologically relevant approach to tackling the problem of eutrophication.

In the shallow water habitats of the coastal zone, benthic infauna play a central role in the biotic and abiotic functioning of coastal waterbodies, occupying key roles in benthic-pelagic coupling of food webs, enhancing biogeochemical cycling, and often as direct harvest for coastal fisheries (e.g., Chardy and Dauvin, 1992, Michaud et al., 2006, Laverock et al., 2014, Wolkovich et al., 2014, Day et al., 2020). The effects of sediment organic matter accumulation on benthic infaunal community composition have been well documented in the literature and provide an established, predictive conceptual model of the decline and potential recovery of community structure and function in systems across the globe (Pearson and Rosenberg, 1978, Kalantzi and Karakassis, 2006, Gray et al., 2002, Rakocinski, 2012, Tagliapietra et al., 2012, Keeley et al., 2015, Cranford et al., 2020). The production and accumulation of labile organic matter associated with eutrophication stimulates heterotrophic bacterial communities in sediments, increasing water column and benthic oxygen demand (Lavery and McComb, 1991, Diaz and Rosenberg, 1995, Baustian and Rabalais, 2009), while simultaneously decreasing sediment redox potential (Cardoso et al., 2004). Zones of sediment anoxia and sulfate reduction become shallower across the sediment horizon, often extending to the sediment–water interface (Dauer et al., 1981, Hentschel, 1996). This leads to an increase in pore water ammonia and sulfide concentrations that are toxic to the benthic fauna (Giordani et al., 1996, Kristiansen et al., 2002). Tolerance to changes in organic matter concentrations and low oxygen conditions varies widely among the taxonomically diverse macrobenthic community, though persistent anoxic conditions will eventually kill all metazoans (Holland et al., 1977, Diaz and Rosenberg, 2008, Rabalais et al., 2010). In habitats or environmental settings where eutrophication-driven hypoxia and anoxia are less important to the benthos, the primary mode of impact from eutrophication then becomes the accumulation of toxic reduced compounds in the sediment from bacterial metabolism of organic matter (Karakassis et al., 1999, Kalantzi and Karakassis, 2006, Shin et al., 2006, Cranford et al., 2020).

The majority of studies characterizing the relationship between the macrobenthos and eutrophication have centered on the faunal "side" of the relationship, describing compositional changes along gradients of eutrophic stress. Thresholds of sediment organic matter concentration protective of the integrity of macrobenthic community composition have only been identified in a handful of studies (Hyland et al., 2005, Diaz et al., 2008, Magni et al., 2009, Pelletier et al., 2011). The results of these studies from coastal and lagoonal systems across the Northern Hemisphere identified values between 10 and 35 mg g^{-1} (DW) of sediment total organic carbon (TOC) as protective of benthic community condition. It is important to note that sediment TOC values do not always reflect eutrophic stressor exposure in estuarine sediments that receive significant terrigenous inputs of refractory organic matter. In contrast, sediment total nitrogen (TN) is an overlooked indicator that more directly measures response of the ecosystem to anthropogenic nitrogen loading (Gillett, 2010). Most studies considered TOC concentrations across all sediment environments, but Pelletier et al. (2011) differentiated the organic matter impacts in relation to the sediment composition. Sediment grainsize can be an important factor in the carrying capacity or resistance of a given location to organic matter additions and how deleterious they may be to the resident fauna (Gillett, 2010).

Many countries and U.S. states, including California, have shifted the focus of their environmental policies to protect the structure and function of biotic resources (i.e., biointegrity) versus simple pollutant concentrations (California Regional Water Quality Conrol Board San Diego, 2020; Agency, 2000; ANZCC, 1992), which has led to changes in the monitoring and regulating of stressors like eutrophication in the environment. Macrobenthic infauna are one the most common faunal assemblages used to assess habitat quality in the coastal oceans of the world (e.g., Gibson et al., 2000, Diaz et al., 2004) due to their relatively sessile lifestyle, taxonomic diversity, and ability to integrate stressor exposure over time (Dauer, 1993, Gray et al., 2002, Gray and Elliott, 2009, Pelletier et al., 2010). Within California's coastal waters, considerable advances have been made in identifying sediment quality targets for traditional toxic contaminants and their effects on benthic and nektonic fauna (Ritter et al., 2012, Bay et al., 2021, Parks et al., 2021). Less progress has been made on the science to inform eutrophication targets protective of benthic habitat quality in estuaries, a key science gap that could guide the derivation of nutrient loading targets through observational and computational models.

To address this knowledge gap, we undertook a study to identify thresholds of sediment organic matter concentrations associated with changes in macrobenthic community composition across the euhaline estuaries and embayments of the Southern California Bight (SCB, Fig. 1). Our goals were to: 1) develop statistical models that describe the stressor-response relationship between eutrophication-driven sediment organic matter (stressor) and macrobenthic community integrity (response); 2) identify numeric thresholds from these models that correspond to probabilities of attaining management goals for biological integrity; 3) compare these values to numbers derived from other threshold-setting approaches used to set water quality goals; and 4) to assess the extent of habitat in southern California estuaries and embayments that exceed these thresholds and therefore could be considered at risk for eutrophication impacts to biointegrity. We hypothesized that, following an initial no effect zone (reference envelope), we would see a decline in macrobenthic community condition with increasing organic matter accumulation (sensu Pearson and Rosenberg, 1978, Gray et al., 2002). Our ultimate objective is to provide policymakers with information to set numeric eutrophication targets that are likely to protect biointegrity goals. Throughout, "thresholds" refer to numeric eutrophication values derived through scientific analyses that achieve a range of biointegrity goals, whereas "targets" refer to management or policy decisions. The use of the term goal in relation to biointegrity does not imply a management or policy decision.

2. Methods

2.1. Conceptual approach

Macrobenthic community composition and sediment chemistry (e.g., TOC, TN, toxic contaminants) data, as well as general environmental data (habitat type, grainsize composition, water depth) for estuaries and coastal embayments were obtained from the 1998 – 2013 Southern California Bight Regional Monitoring Program (SCB RMP; Schiff et al., 2016). Benthic community condition was quantified using the M-AMBI condition assessment tool modified for application in estuarine waters of the United States (Pelletier et al., 2018). Benthic community condition was related to sediment TOC or TN content using logistic regression, with the probability of desirable benthic condition predicted by sediment organic matter. Sediment organic matter thresholds were derived, corresponding to several relative probabilities (from 0.6 to 0.8), reflecting a range of policy makers' potential tolerance for risk of failing to meet biointegrity goals. To minimize the influence of sediment contaminants on the potential benthos-organic matter relationships, data were screened to remove highly contaminated sediments prior to analysis. Thresholds were subsequently validated with data from the 2018 SCB RMP, comparing the expected condition of samples based upon sediment organic matter content to that of the actual observed condition. Because biological goals are ultimately policy decisions, we compared thresholds derived from the logistic regressions (i.e., based on changes in M-AMBI benthic index scores) with thresholds compared to taxon-specific patterns derived from abundance-based changepoint analysis.

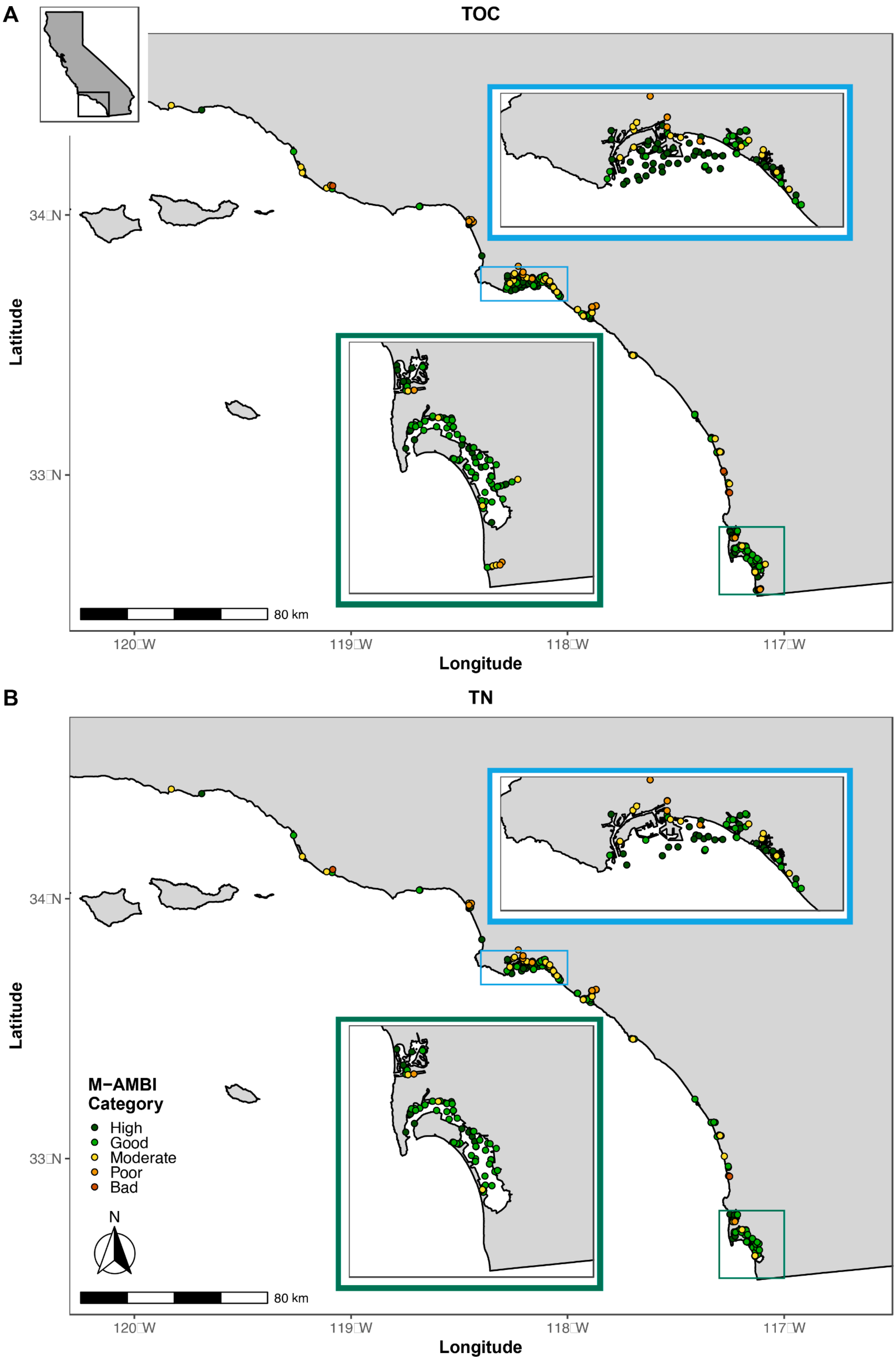

Fig. 1. Map illustrating the distribution of benthic samples with sediment TOC (A) and TN (B) measurements across the Southern California Bight (samples containing elevated levels of toxic contaminants were excluded). The points illustrate the distribution of organic matter concentration for each M-AMBI category – High (dark green), Good (green), Moderate (Yellow), Poor (Orange), and Bad (Red). The inset in the upper left of figure A shows the location of the region relative to the Pacific Coast of California. The blue outlined insets provide a detail of San Pedro Bay, the ports of Long Beach, and Los Angeles, CA. The green outlined insets provide a detail of Mission and San Diego bays. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Datasets

All data were obtained from the SCB RMP (Schiff et al., 2016, Fig. 1). The survey uses a probabilistic, stratified random design (Stevens and Olsen, 2004, Olsen and Peck, 2008) to collect benthic infauna and sediment chemistry data in a variety of coastal and oceanic habitats from Point Conception, CA to the US-Mexican border at five-year intervals beginning in 1998. Both benthic community and sediment chemistry data were obtained from 905 samples collected from coastal embayments and estuaries collected during July to September of 1998, 2003, 2008, and 2013 across the breadth of the SCB (Fig. 1; https://www.sccwrp.org/about/research-areas/data-portal/). Within the SCB RMP, embayments were defined as naturally occurring Bays (e.g., San Diego Bay) or artificial ports and marinas (e.g., San Pedro Bay). Estuaries included permanently open and ephemeral/bar built estuarine waters with salinity greater than 27 PSU at time of sampling (Gillett et al., 2017).

2.3. Benthic infauna

Benthic infauna sample collection, identification, and enumeration followed Gillett et al. (2017). In brief, sediment samples were collected with a 0.1 m^2 Van Veen grab, sieved on a 1 mm screen and preserved in a 10% formalin solution buffered with seawater. Organisms were sorted from the preserved material, enumerated, and identified to the lowest possible taxonomic level (typically species). Species names from the different sampling events were harmonized to match the SCAMIT ed12 species list (The Southern California Association of Marine Invertebrate Taxonomists, 2018) to ensure comparability. Condition of the benthic community was quantified using the Multivariate ATZI-Marine Biotic Index (M-AMBI) of Pelletier et al. (2018) modified for application in estuarine waters of the US. The M-AMBI categorizes samples into five condition categories: High, Good, Moderate, Poor, or Bad condition.

2.4. Sediment chemistry and composition

Methods for processing and measuring samples for sediment contaminants, grainsize composition, and TOC and TN content followed Dodder et al. (2016). Sediment contaminants included a suite of compounds typically measured in regional surveys: heavy metals, polychlorinated biphenyls (PCBs), polynuclear aromatic hydrocarbons (PAHs), and pesticides. Briefly, grainsize samples were sieved on 2-mm and 1-mm screens to capture the gravel fraction and the remaining smaller particles were analyzed using a SM2560D laser refractometer. Sediments for TOC and TN analysis were acidified with hydrochloric acid vapors and combusted in a high temperature elemental analyzer with a gas chromatograph. Samples for all metals except for mercury were digested in a strong acid, with the digestate analyzed by inductively coupled plasma mass spectrometry. Mercury was analyzed using cold vapor atomic adsorption spectroscopy. The trace organics (PAHs, PCBs, and pesticides) were solvent extracted and analyzed with gas chromatography mass spectrometry. For more details regarding processing and measuring sediment samples, refer to Dodder et al. (2016).

2.5. Statistical analyses

To minimize the potential influence of any toxic chemicals on benthic community composition and thereby obscure any relationships with TOC or TN, highly contaminated samples were removed prior to the stressor-response analyses. The degree of potential exposure to sediment contaminants within each sample was defined using the California Chemical Stressor Index (CSI; Ritter et al., 2012, Bay et al., 2021). The CSI uses measures of metals, PCBs, PAHs, and DDTs to categorize sediments into categories of potential exposure for benthic infauna – Minimal Exposure, Low Exposure, Moderate Exposure, or High Exposure. Any sample within the High Exposure category was removed from any subsequent analysis (40 samples). Similarly, to control for the influence of sediment grainsize on macrobenthic community composition – organic matter content relationships, samples were divided into those from sandy ($\geq$60% sand content) or muddy sediments (<60% sand content). Relationships between raw M-AMBI scores and organic matter concentrations were evaluated using Spearman's Rho correlation.

Logistic regression was used to quantify the relationship between benthic community condition and different levels of TOC or TN. Samples were classified as being in either good biological condition (M-AMBI categories of High or Good) or poor condition (M-AMBI categories of Moderate, Poor, or Bad). Logistic regression models were created with the probability of good macrobenthic community condition as the response variable and TOC or TN concentration as the predictor variable. Separate models were run for each organic matter parameter and sediment type (Sand or Mud). Significant logistic regression models ($\alpha = 0.1$) for each combination of sediment and organic matter type were then used to identify concentrations of that were predictive of a ≥ 0.6, $\geq$0.7, or ≥ 0.8 probabilities of good condition benthic fauna occurring. An $\alpha = 0.1$ was chosen apriori based upon the authors' tolerance for Type I error in regression models of non-controlled environmental data. Logistic regressions were conducted with the glm function in R (v 4.0.2, R-Core-Team, 2020) using a binomial distribution and a logit link.

Threshold Indicator Taxa Analysis (TITAN; Baker et al., 2015) was used to characterize taxon-to-taxon differences in the response to increasing sediment TOC and TN content. TITAN identifies numeric values along gradients where taxa exhibit a change in their abundance (either increasing or decreasing) and is an extension of indicator species analysis (Dufrêne and Legendre, 1997). TITAN calculates changepoints along a gradient of disturbance (TOC or TN in this study) for each taxon and classifies it as an increaser or a decreaser. These changepoints were compared to the different TOC and TN thresholds derived from the M-AMBI−based logistic regression. Calculations were made with the TITAN2 package in R (v2.4.1; Baker et al., 2015). Taxa appearing in <5% of sites were excluded from analysis.

Each of the different thresholds for TOC and TN derived from the logistic regression models were validated with samples from the 2018 SCB RMP. The observed condition of macrobenthic samples were compared to the condition predicted by the organic matter thresholds, where greater than the threshold = an expectation of poor condition macrobenthos and less than the threshold = an expectation of good condition benthos. Observed condition vs predicted condition counts were arrayed in 2×2 contingency tables from which the overall percent of correct predictions, the false positive rate, and the false negative rate were calculated (e.g., Fawcett, 2006). Given that the models were designed to predict macrobenthic communities in good condition, a false positive was defined as an instance where the TN or TOC concentrations in the sediment were below the threshold, but the macrobenthic community was not in good condition. In contrast, a false negative was an instance where the TN and TOC concentrations were above the threshold, but the macrobenthic community was in good condition.

3. Results

Of the 905 samples from across the region, 865 samples were used in the analyses (Fig. 1). M-AMBI scores in samples from sediments exhibited negative, but noisy, relationships with both TN and TOC – r_s TN in mud = −0.303 ($n = 308$, $p < 0.001$), r_s TN in sand −0.004 ($n = 60$, $p = 0.98$); r_s TOC in mud = −0.279 ($n = 408$, $p < 0.001$); r_s TOC in sand = −0.012 ($n = 89$, $p = 0.93$; Fig. 2). The left-handed wedge-shaped distributions suggest that other stressors (e.g., habitat alteration, water quality) may be limiting biointegrity at some sites, even when eutrophication pressure are low. High biointegrity scores were sometimes observed at sites with high eutrophication pressure, but these observations were comparatively rare and possibly related to stimulation effects. For purposes of the logistic regression, 83% of the samples with TN measurements were in good condition (M-AMBI category High or Good)

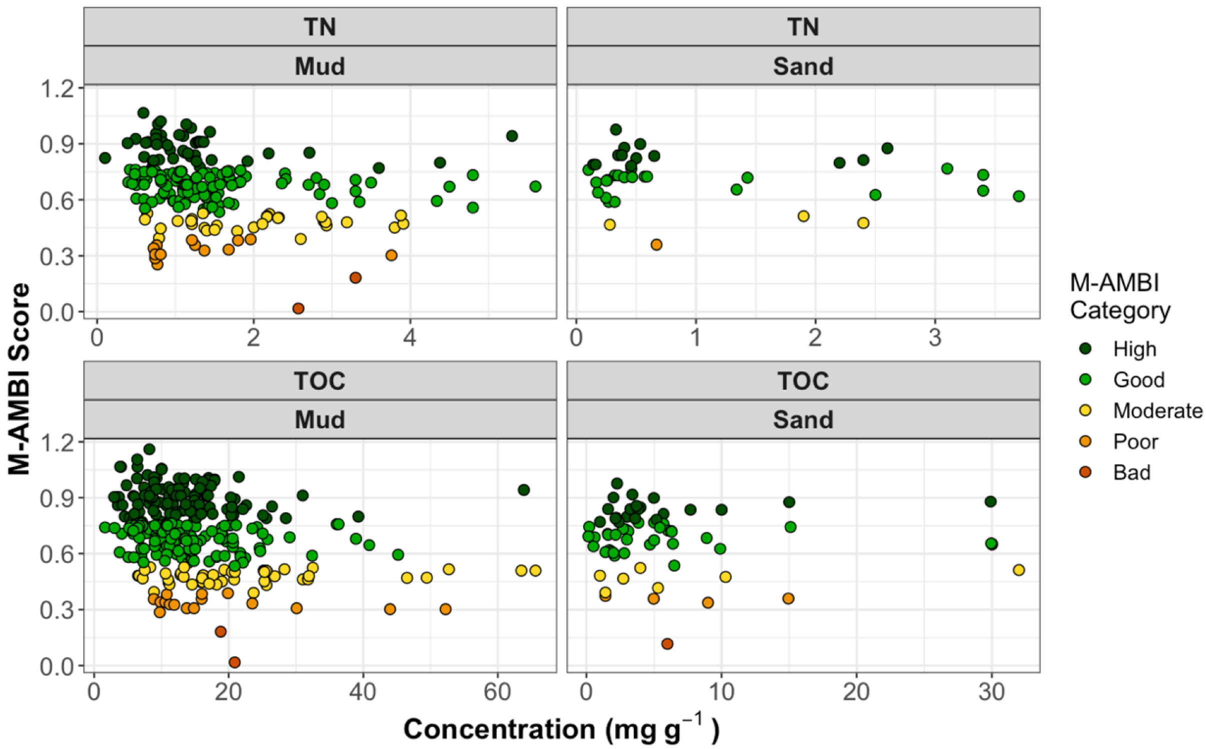

Fig. 2. Scatterplots of M-AMBI scores as a function of concentration of TOC and TN in muddy or sandy sediments. The color of the dots indicates the M-AMBI categorical classification for each sample. Note that lower M-AMBI scores indicate poorer condition.

as were 82% of samples with TOC measurements.

There were significant ($\alpha = 0.1$), albeit noisy, inverse relationships between the probability of good macrobenthos and increasing concentration of TOC and TN in muddy sediments (Table 1, Fig. 3). However, in the sandy sediment samples, no clear relationships were found between macrobenthic community condition and either TOC or TN. The significant models from the muddy sample regressions were used to extract TN and TOC values that would be predictive of observing good condition macrobenthic communities at 0.8, 0.7, and 0.6 probabilities (Table 2). Concentrations of TOC and TN were calculated using the logistic regression equation rearranged to solve for × (Equation (1)), where *p(x)* is the probability of observing a good condition macrobenthic community, Intercept = y-intercept (β_0) from the logistic regression model, and β = the slope estimate from the logistic regression model.

$$[OrganicMatter] = (\ln\frac{p(x)}{1-p(x)} - Intercept)/\beta \quad (1)$$

Given the non-significant relationships between macrobenthic condition and organic matter in the sandy sediment samples, the TITAN changepoint analysis was only run with muddy sediment samples. The TITAN analyses classified nearly all of the taxa it could model as decreasing in abundance with increasing amounts of either TN (43 taxa) or TOC (90 taxa). There were only 3 increasing taxa with TN and 22 with TOC. Details are provided in Supplementary Material 1. When the changepoints of all the taxa were visualized together (Figs. 4 and 5), the first major discontinuity in changepoints for the loss of for sensitive taxa (<0.8 mg g $^{-1}$ TN and < 15 mg g-1 TOC) roughly corresponded to the TOC and TN values at the 0.8 probability threshold from the logistic regression models. Decreasing taxa included a mix of cumaceans, mysids, and amphipods, predatory polychaetes, filter/interface feeding polychaetes and bivalves. The second major discontinuity in changepoints representing a more substantial loss of the diversity occurred at levels greater than 1.8 mg g^{-1} TN and greater than 25 mg g^{-1} TOC, after which traditionally organic matter tolerant and surface/subsurface deposit feeding species (e.g., *Capitella capitata*, cirratulid polychaetes, corophiid amphipods) dominated. The 25 mg g^{-1} TOC value was similar and associated with the 0.7 probability from the M-AMBI logistic regression, but the 1.8 mg g^{-1} TN value was lower than the 0.7 probability equivalent.

Across Southern California estuaries and embayments ~4% and ~5% of samples exceeded the 0.6 probability threshold for TN and TOC, respectively (Table 3, Fig. 6), while 10% of samples exceeded the 0.7 probability threshold for both TN and TOC, and 35% and 28% of samples exceeded 0.8 probability threshold for TN and TOC, respectively. Because of the need to assess all areas, the mud thresholds were applied to the sandy sites. The most degraded sites were located within estuaries and enclosed bays, relative to open embayment sites in coastal SCB (Fig. 1).

When the muddy sediment TOC and TN 0.6, 0.7, and 0.8 thresholds were applied to a naive validation dataset (data from the 2018 SCB RMP) the different thresholds correctly classified between 67 and 86% of samples (Table 4). The TN thresholds tended to have greater accuracy than the TOC thresholds. The proportion of false negatives to false positives among the misclassified samples changed with the value of the TN/TOC threshold. The more stringent 0.8 probability thresholds had higher false negative rates (i.e., predicted to be in bad condition, but observed in good condition), while the 0.6 probability thresholds had higher false positive rates (i.e., predicted to be in good condition, but

Table 1
Statistical summary of the logistic regression models of the probability of observing benthic community samples in good condition (M-AMBI High or Good category) as a function of TN and TOC concentration in sandy or muddy estuarine and embayment sediments of Southern California.

Parameter	Sediment Type	n	Intercept	Beta	F-statistic	*p*-value
TN	Mud	308	1.88	−0.400	−2.62	0.009
TN	Sand	60	2.44	−0.239	−0.54	0.587
TOC	Mud	408	2.52	−0.073	−4.82	<0.001
TOC	Sand	89	1.72	−0.027	−0.72	0.469

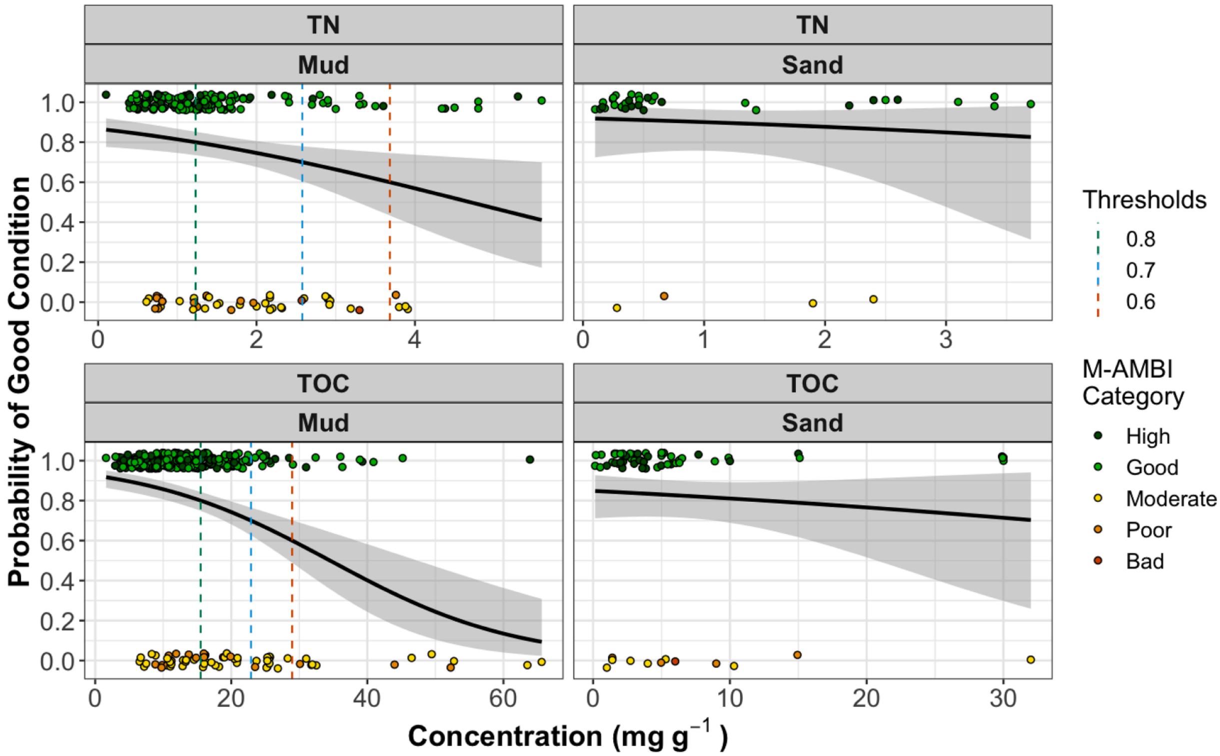

Fig. 3. Logistic regression curves illustrating the probability of a benthic community being in good condition (High or Good M-AMBI condition categories [Pelletier et al., 2018]) along a gradient of TOC or TN in mud or sand sediments. The points in the rug illustrate the distribution of organic matter concentration among good condition and bad condition samples for each regression. Points are color-coded to indicate their M-AMBI category classification and are vertically jittered for ease of visualization. The vertical lines indicate the different TOC or TN thresholds derived from the logistic regression models that were predictive of a 0.8 (green), 0.7 (blue), and 0.6 (red) probability of observing a good condition benthic sample given that amount of TOC or TN (Table 2). Note that thresholds were not derived from the sandy sediment models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
TN and TOC values (mg g^{-1}) estimated from the logistic regression models of Table 1 that were predictive of 0.6, 0.7, or 0.8 probabilities of observing benthic communities in good condition. Sandy sediment models for TOC and TN were not significant based upon our apriori $\alpha = 0.1$ and therefore we chose to not estimate values from those models.

Parameter	Sediment Type	0.6 Probability	0.7 Probability	0.8 Probability
TN	Mud	3.68	2.58	1.23
TN	Sand	–	–	–
TOC	Mud	28.96	22.90	15.51
TOC	Sand	–	–	–

observed in bad condition). The overall high false-positive rates across all of the threshold options were most likely indicative of other non-eutrophication stressors affecting macrobenthic community condition.

4. Discussion

Effective ecological indicators can be evaluated by the degree to which they: 1) are cost-effective and easy to measure, 2) capture changes in ecosystem integrity or function, 3) permit examination of responses and linkages to stressors at various spatiotemporal scales, 4) have scientific consensus on thresholds through which to evaluate ecological status and 5) are amendable to validation of reliability through quantitative assessments of sensitivity and background variability (Rakocinski and Zapfe, 2005). Macrobenthic community structure provides a reliable indicator of estuarine biological integrity, interpreted through condition assessment indices such as M-AMBI (Diaz et al., 2004, Ranasinghe et al., 2009). However, their utility in fixing problems can be limited without thresholds to diagnose specific causes of impairment, such as toxic contaminants, physical habitat disturbance, or eutrophication-driven organic matter accumulation. Sediment TOC and TN concentrations are a routine and reliable measure of eutrophication in shallow, soft sediment habitats and are often more relevant to macrobenthic health than water column measures of nitrogen or phosphorus (Dauwe et al., 1998, Edgar et al., 2005, Zhang and Wirtz, 2017, Brugnoli et al., 2021). However, scientific consensus on sediment TOC and TN thresholds that are protective of benthic habitat quality have been lacking.

Our study documented the decline in macrobenthic community condition with increasing gradients of sediment organic matter in the SCB coastal embayments and estuaries, findings consistent with a well-established, predictive conceptual models widely accepted across the globe (Pearson and Rosenberg, 1978, Giordani et al., 1996, Kristiansen et al., 2002, Kalantzi and Karakassis, 2006, Gray et al., 2002, Rakocinski, 2012, Tagliapietra et al., 2012, Keeley et al., 2015, Cranford et al., 2020). From logistic regression models, we identified then validated sediment TOC and TN thresholds protective across a range of prescribed probabilities of achieving good benthic habitat quality using the M-AMBI index. Our data would suggest that sediments with more than 15.5 mg g^{-1} TOC or 1.2 mg g^{-1} TN have a reduced likelihood of supporting a desirable, intact benthic community (i.e., that which

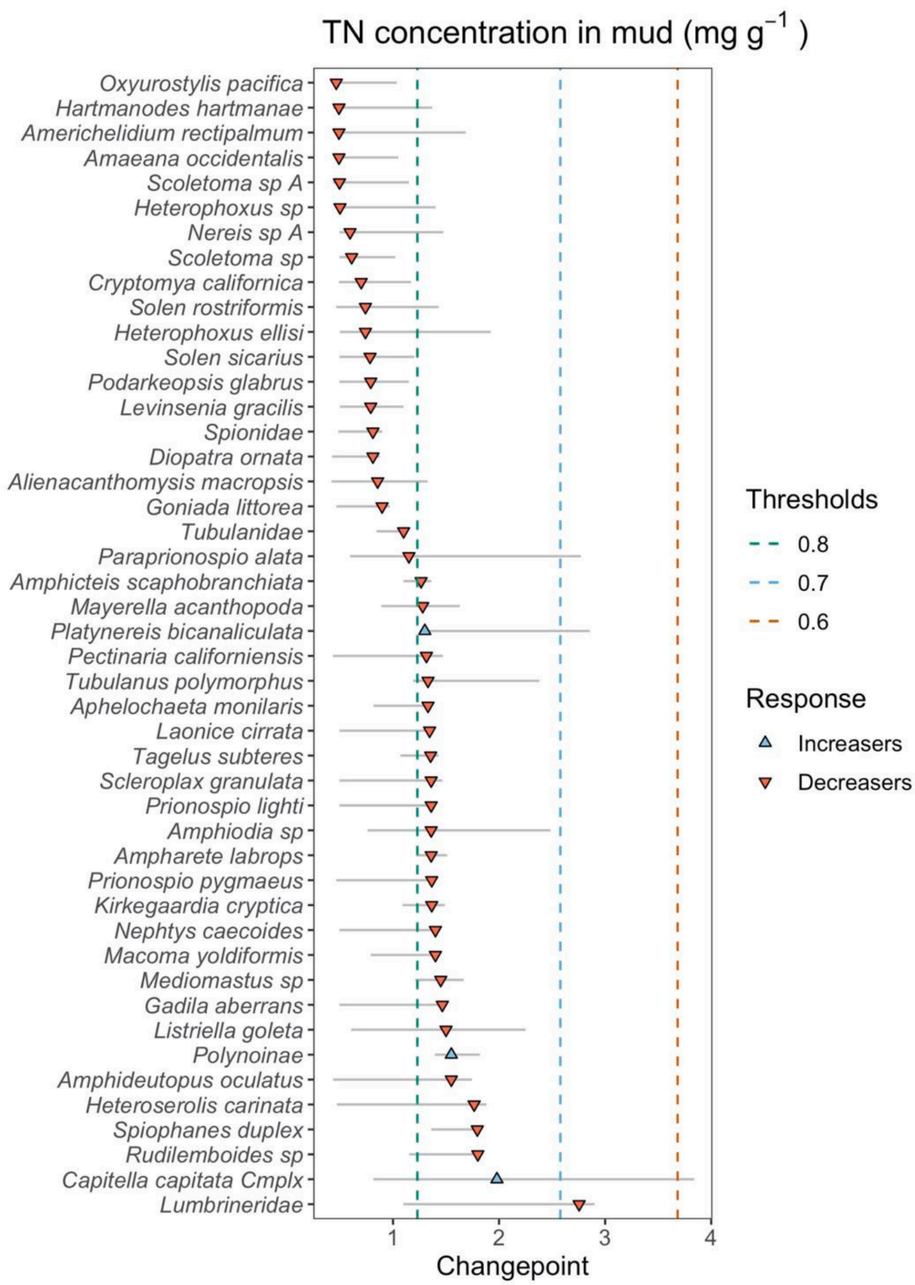

Fig. 4. TITAN changepoint analyses for macrobenthic community assemblage changes as a function of increasing TN concentration (mg g^{-1}). Blue symbols are species that increased with increasing TN, while red symbols are those that decreased. Dashed vertical lines correspond to logistic regression thresholds for probabilities of 0.6, 0.7, and 0.8 of achieving a good or high M-AMBI score. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

produces High or Good category M-AMBI scores). Further along the eutrophication gradient, sediments in excess of 28.9 mg g^{-1} TOC or 3.7 mg g^{-1} TN have a minimal likelihood of supporting a desirable, intact community. The TOC thresholds identified from our Southern California dataset fell within a similar range (10 – 35 mg g^{-1}) that has been linked to benthic community impacts from a variety of coastal ocean sites across the Northern Hemisphere (Hyland et al., 2005, Diaz et al., 2008). Similarly, Magni et al. (2009) determined that TOC values greater than 28 mg g^{-1} were deleterious to benthic community diversity in the lagoonal systems of Italy. Building on this conceptual model, the agreement between our results and those in the literature (Hyland et al., 2005, Magni et al., 2009, Green et al., 2014, Sutula et al., 2014) would suggest that there may be similarly applicable community-degradation thresholds across temperate estuaries of the world for sediment TOC and TN. As such, the thresholds presented in this study and the others from the literature could potentially be used as a guideline in the management of eutrophication stressors in temperate coastal and inshore systems across the globe.

Studies quantitatively linking sediment TN content to macrobenthic community health are largely absent in the literatures; this study is the first to put forth a series of sediment TN thresholds protective of benthic community condition. We would further suggest that TN measurements are potentially more important for monitoring benthic community health in relation to eutrophication. Sediment TN tends to be highly labile and indicative of recent and biogeochemically active organic material versus TOC content, which can be more recalcitrant and decoupled from eutrophication dynamics (e.g., Tenore, 1988, Asaoka et al., 2020). This was illustrated by the slightly better predictive power of TN values with regard to macrobenthic community condition in the validation dataset. Interestingly, the concentration of TN linked to degraded benthic community condition, as well as the TOC values, are similar in magnitude to those observed by Sutula et al. (2014) to be linked to elevated densities of macroalgae in California embayments and estuaries. The concordance between sediment TOC and TN values

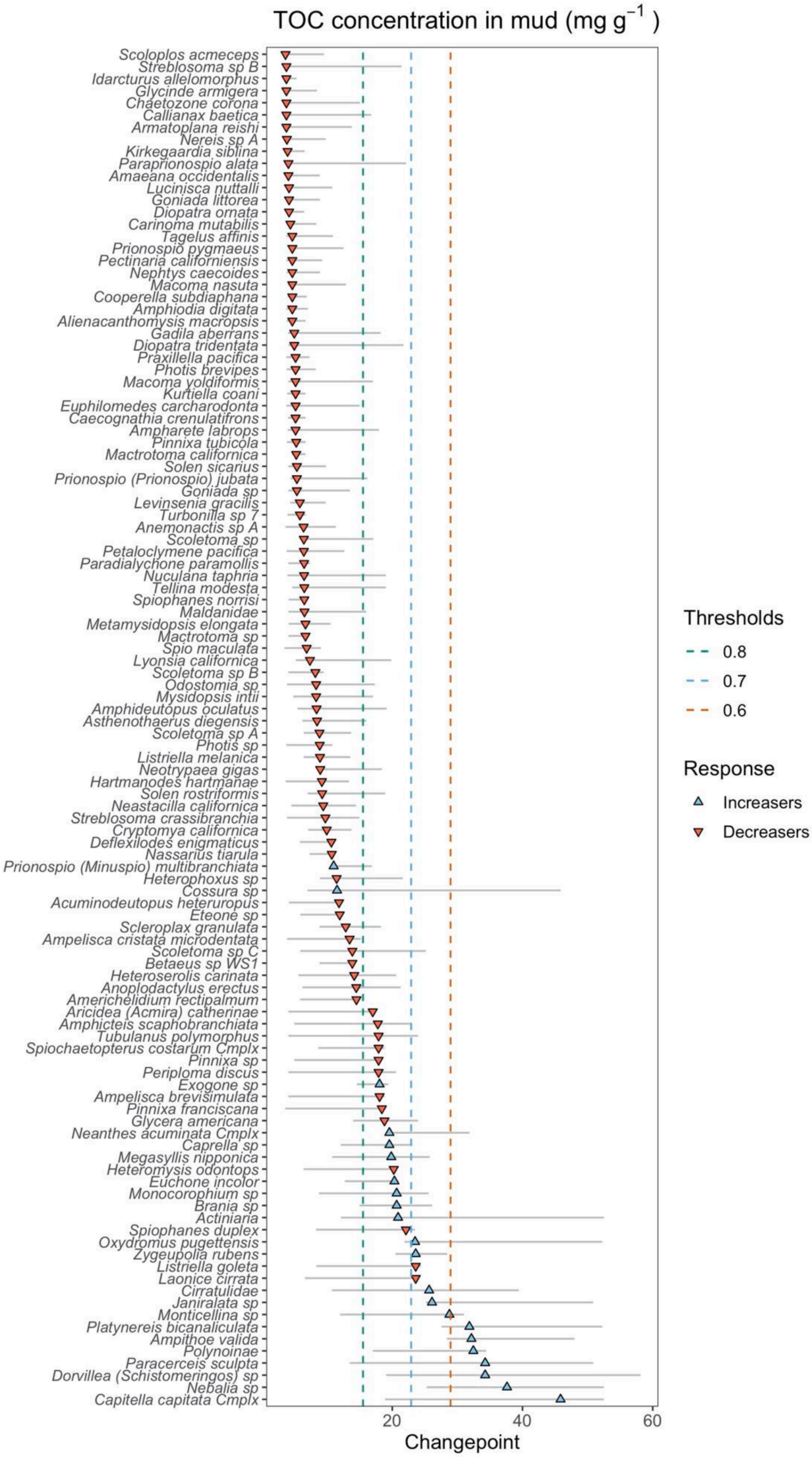

Fig. 5. TITAN changepoint analyses for macrobenthic community assemblage changes as a function of increasing TOC concentration (mg g^{-1}). Blue symbols are species that increased with increasing TOC, while red symbols are those that decreased. Dashed vertical lines correspond to logistic regression thresholds for probabilities of 0.6, 0.7, and 0.8 of achieving a good or high M-AMBI score. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
An inventory of SCB samples from muddy or sandy environments that would be above the thresholds for the respective probabilities of observing good condition macrobenthic communities for the corresponding amounts of TOC or TN (Table 2). Thresholds from the mud logistic regression models were applied to sandy sediment samples as there were no appropriate thresholds for sandy sediments.

Sediment Type	OM Type	Above 0.8 Threshold	Above 0.7 Threshold	Above 0.6 Threshold
Mud	TN	51.9%	15.5%	5.3%
Mud	TOC	37.9%	14.4%	7.2%
Sand	TN	30.8%	12.8%	2.6%
Sand	TOC	7.4%	7.4%	7.4%

predictive of two different impacts of eutrophication (macrobenthic degradation and increases in nuisance algae) lend credence to the validity of these thresholds as meaningful indicators of ecosystem change.

Bioassessment indices like the M-AMBI provide a repeatable, integrative, and holistic measure of habitat condition based on assemblage structure, but they may lack the ability to capture the responses of the most sensitive species within the assemblage (Baker and King, 2013). In contrast, taxa-focused approaches to assessment like TITAN can often provide insight into the responses of individual taxa across many samples. The results from the TITAN analyses would suggest the community loses high-metabolism crustaceans and larger bodied organisms early along the gradient of eutrophication, then the predators, omnivores, and filter-feeding bivalves, until the last taxa, which tended to be those increasing in abundance, are the surface and sub-surface deposit feeders. This pattern broadly followed the shifts in community composition that

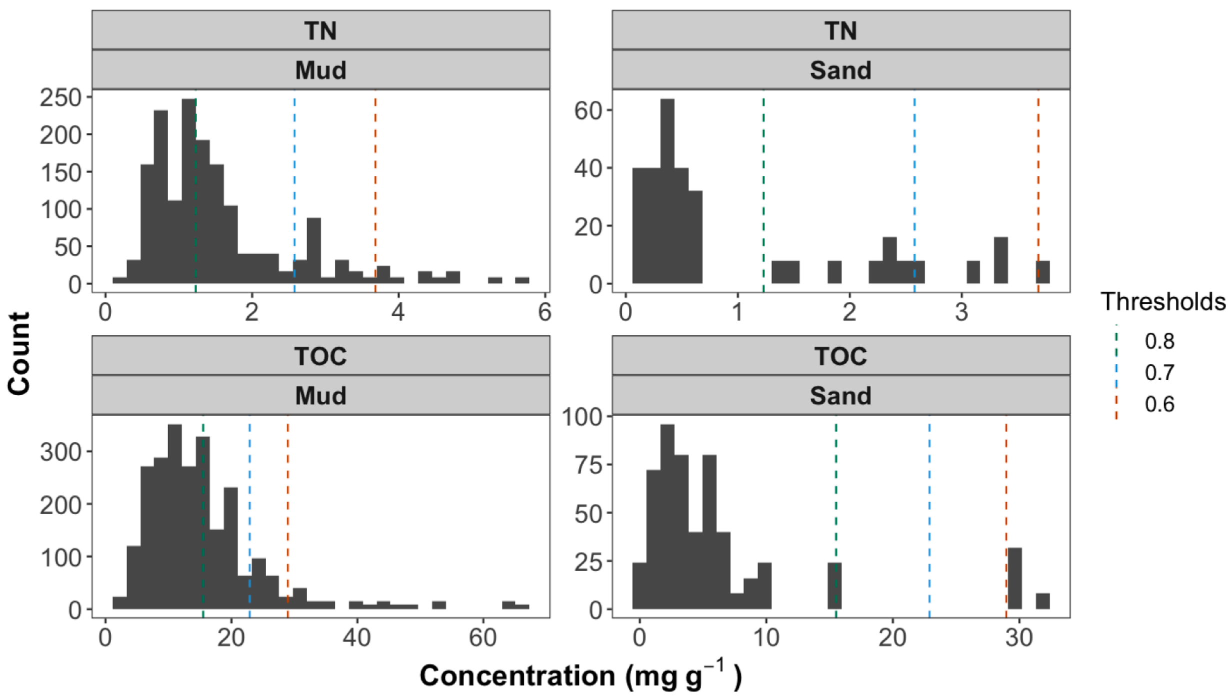

Fig. 6. Histograms of sediment TOC and TN concentrations observed across the muddy and sandy sediments of our SCB data set (highly contaminated samples excluded). The vertical dashed lines indicate the different thresholds derived from the logistic regression models that were predictive of a 0.8 (Green), 0.7 (Blue), and 0.6 (Red) probability of observing a good condition benthic sample given that amount of TOC or TN. Thresholds from the mud logistic regression models were applied to sandy sediment samples as there were no appropriate thresholds for sandy sediments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
2 × 2 Contingency tables and summary statistics comparing observed macrobenthic community condition (rows) to that predicted by TOC and TN thresholds (columns) (Table 2) associated with 0.8 (A), 0.7 (B), or 0.6 (C) probabilities of observing good condition macrobenthic communities. Contingency tables are presented as percentages of the 2018 validation samples. There were 174 samples with TOC measurements and 144 with TN measurements.

A		% Above Threshold	% Below Threshold	% Correct	False Positive Rate	False Negative Rate
TOC	Bad Condition	4.6	9.2	67.2	0.67	0.27
	Good Condition	23.6	62.6			
TN	Bad Condition	7.6	8.3	72.2	0.52	0.23
	Good Condition	19.4	64.6			
B		% Above Threshold	% Below Threshold	**% Correct**	**False Positive Rate**	**False Negative Rate**
TOC	Bad Condition	2.9	10.9	78.2	0.79	0.13
	Good Condition	10.9	75.3			
TN	Bad Condition	3.5	12.5	85.4	0.78	0.03
	Good Condition	2.1	81.9			
C		% Above Threshold	% Below Threshold	**% Correct**	**False Positive Rate**	**False Negative Rate**
TOC	Bad Condition	2.9	10.9	81.6	0.79	0.12
	Good Condition	10.9	78.7			
TN	Bad Condition	2.1	13.9	86.1	0.87	0.00
	Good Condition	0	84			

would be predicted from macrobenthos-eutrophication conceptual models (e.g., Pearson and Rosenberg, 1978, Gray et al., 2002) and matches quite well with the underlying conceptual model of the M-AMBI (Borja et al., 2000, Muxika et al., 2007). This concordance is why there was relatively good agreement between the major community inflection points from TITAN and the 0.8 and 0.7 probability thresholds from the M-AMBI logistic regression models.

We identified thresholds of benthic community impact from TOC or TN in muddy (i.e., <60% sand content) sediments, but were unable to create any statistically meaningful logistic models in sandy sediments due, in part, to their relatively low frequency of occurrence in our dataset compared to the muddy sediments (Table 1) and the absence of a strong gradient in benthic community condition across those samples (Fig. 2). Sediment composition is one of the major factors influencing the types of benthic fauna that can live in a given location (Snelgrove and Butman, 1994, Anderson, 2008, Henkel and Politano, 2017), but it may also serve to either buffer or exacerbate the effects of eutrophication and organic matter on the benthic community. On the whole, the benthic community's response to increasing eutrophication tends to be negative. However, in sandy sediments, where there is less natural organic matter accumulation, eutrophication may initially act as positive subsidy to the benthos, improving community diversity, abundance, and biomass/productivity (Rakocinski and Zapfe, 2005, Rakocinski, 2012, Tagliapietra et al., 2012). That being said, the right types of fauna (e.g., filter or interface feeders) that can take advantage of any supplemental organic matter delivered to system, do need to be present in the community to realize the positive benefits of eutrophication (Gillett, 2010).

The distribution of benthic index scores along the gradients of TOC and TN in both sandy and muddy sediments– particularly the presence of degraded condition samples at low levels of organic matter – and the relatively high false positive rates in our validations are suggestive that we were not able to establish a gradient of eutrophication stress alone within our dataset. Most estuaries and embayments of southern California where these data came from are pervasively altered (e.g., dredging, hardened shorelines, recreational or commercial piers) and may be exposed to contaminants that are not accounted for in our data screening process (e.g., pyrethroids, PBDEs; Du et al., 2020). These other types of stress most likely influenced the condition assessment scores used in our calibration and validation analyses.

5. Conclusions

Using a robust benthic monitoring data set from estuaries and embayments of the SCB, we were able to derive a series of thresholds for sediment TOC and TN that were predictive of healthy and intact macrobenthic communities in the muddy sediments of estuaries and coastal embayments. The TOC thresholds predictive of healthy benthic communities were similar to those observed in estuaries in other parts of the world. Both of the macrobenthos-derived TOC and TN thresholds were similar to those related to and derived from patterns of macroalgal growth/accumulation. The consistency in thresholds across multiple habitats and different types of biota is suggestive of a general, quantitative threshold for organic matter accumulation in near shore sediment habitats and could be useful for informing the management of coastal ecosystems and setting targets biostimulatory stressors in these systems.

The selection of TOC and TN targets for management applications in the coastal zone, from either our macrobenthos-based logistic regression models or other means, is ultimately a policy decision. That being said, it is our opinion that the science presented within this manuscript illustrates the tradeoffs involved in setting management targets – both from quantitative (false positive vs false negative rates) and ecological (shifts in community composition and diversity loss) perspectives. This work represents one piece to be considered in building scientifically sound and practically achievable management goals towards protecting the ecosystems of the coastal zone.

CRediT authorship contribution statement

Janet B. Walker: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **David J. Gillett:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision. **Martha Sutula:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Regional survey data are available from https://www.sccwrp.org/about/research-areas/regional-monitoring/southern-california-bight-regional-monitoring-program/bight-program-data-portal/.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109404.

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