Identifying variables for standardization of the Northern Abalone (Haliotis kamtschatkana) Index Site Surveys time series (1978-2018) based on survey methodology and environmental variability

Sandra C. Hansen, Shannon G. Obradovich, Christopher N. Rooper, Brenda J. Waddell, Linda M. Nichol, Shaun K. MacNeill, and Leslie L. Barton

Pacific Biological Station
Science Branch, Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, British Columbia V9T 6N7
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IDENTIFYING VARIABLES FOR STANDARDIZATION OF THE NORTHERN ABALONE (*HALIOTIS KAMTSCHATKANA*) INDEX SITE SURVEYS TIME SERIES (1978-2018) BASED ON SURVEY METHODOLOGY AND ENVIRONMENTAL VARIABILITY

by

Sandra C. Hansen, Shannon G. Obradovich, Christopher N. Rooper, Brenda J. Waddell, Linda M. Nichol, Shaun MacNeill, and Leslie L. Barton

Pacific Biological Station
Science Branch, Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, British Columbia V9T 6N7

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ABSTRACT

Hansen, S.C., Obradovich, S.G., Rooper, C.N., Waddell, B.J., Nichol, L.M., MacNeill, S., and Barton, L.L. 2020. Identifying variables for standardization of the Northern Abalone (*Haliotis kamtschatkana*) Index Site Surveys time series (1978-2018) based on survey methodology and environmental variability. Can. Tech. Rep. Fish. Aquat. Sci. 3330: vii + 110 p.

The Northern Abalone (*Haliotis kamtschatkana*) is a culturally and ecologically significant endangered marine snail. This report examines forty years of data from the Northern Abalone Index Site Surveys in British Columbia. Northern Abalone densities were generally insensitive to changes in the number of surveyed index sites and quadrats. There was high imprecision around the mean estimates in both the full and restricted datasets. Inclusion of environmental variables identified with generalized additive modelling in a standardized index yielded small improvements in precision of the annual indices. Trend detection using the existing survey data is limited by the large confidence intervals around the mean densities. Recommendations are to include the full dataset in further analyses, to use a subset of environmental variables to standardize the time series, and to increase the number of index sites surveyed in future Northern Abalone surveys.

RÉSUMÉ

Hansen, S.C., Obradovich, S.G., Rooper, C.N., Waddell, B.J., Nichol, L.M., MacNeill, S., and Barton, L.L. 2020. Identifying variables for standardization of the Northern Abalone (*Haliotis kamtschatkana*) Index Site Surveys time series (1978-2018) based on survey methodology and environmental variability. Can. Tech. Rep. Fish. Aquat. Sci. 3330: vii + 110 p.

L'ormeau nordique (*Haliotis kamtschatkana*) est un gastéropode marin en voie de disparition qui revêt une grande importance culturelle et économique. Le présent rapport se penche sur 40 années de données qui ont été recueillies dans le cadre des relevés aux sites repères effectués en Colombie-Britannique pour l'ormeau nordique. De façon générale, les densités d'ormeaux nordiques ont été insensibles aux variations liées au nombre de quadrats et de sites repères visés par les relevés. Une grande imprécision a entouré les estimations moyennes, et ce, tant dans l'ensemble de données complet que dans l'ensemble de données restreint. L'inclusion de variables environnementales ciblées grâce à des modèles additifs généralisés a généré de petites améliorations en ce qui a trait à la précision des indices annuels. La détection de tendances au moyen des données de relevés existantes est limitée par les grands intervalles de confiance qui sont associés aux densités moyennes. On recommande d'inclure la totalité des données dans les prochaines analyses, d'utiliser un sous-ensemble de variables environnementales pour normaliser les séries chronologiques, et d'accroître le nombre de sites repères visés par les futurs relevés de l'ormeau nordique.

1 INTRODUCTION

The Northern Abalone (*Haliotis kamtschatkana*) is a marine snail, patchily distributed along the coast of British Columbia (BC), Canada (Campbell 2000; Geiger 2000). Northern Abalone is the only species of abalone found in Canada and the species' geographic range extends along the Pacific coast from southeast Alaska to Baja California (Campbell 2000; Geiger 2000). Historically, this species supported First Nations', recreational and commercial fisheries (Sloan and Breen 1988; Farlinger 1990). The commercial fishery for Northern Abalone has operated in BC since the early 1900s, and in the 1970s, landings began to follow the boom and bust trajectory typical of many abalone fisheries across the globe (Breen 1986; Sloan and Breen 1988; Campbell 2000). Concern over drastic declines in the surveyed density of Northern Abalone culminated in a total closure of all fisheries in 1990 (Farlinger 1990; Campbell 2000). The history of the Northern Abalone commercial fishery and management are described in Sloan and Breen (1988), Farlinger (1990), and Farlinger and Campbell (1992).

Despite the closure of the fisheries, surveyed densities of Northern Abalone did not increase (Harbo 1997) and Northern Abalone were first designated as "Threatened" in 1999 by the Committee on the Status of Endangered Species in Canada (COSEWIC) (Jamieson 2001), and re-designated as "Endangered" in 2009 (COSEWIC 2009). Following COSEWIC designation, Northern Abalone were first legally listed as "Threatened" in 2003, and then re-listed as "Endangered" in 2009 under the Species at Risk Act (DFO 2012). In preparation for the upcoming reassessment of Northern Abalone status in Canada, Fisheries and Oceans Canada (DFO) is updating analyses of the trends in surveyed densities, building on the recent analyses of Curtis and Zhang (2018). The DFO Northern Abalone Index Site Surveys are the longest time series available to estimate trends in Northern Abalone densities in BC (1978-present), providing indices of Northern Abalone abundance (e.g., Lessard et al. 2007b; Curtis and Zhang 2018). However, methodological changes, changes in technology, environmental variability, and the inherent patchiness of abalone all contribute considerable variation to density estimates derived from this time series. One method that can be used to reduce variation in abundance surveys, such as this one, is to standardize surveys using appropriate covariates (Maunder and Punt 2004). Standardization using covariates is applied in order to reduce the impact of these sources of variability on the index of abundance (Maunder and Punt 2004). This report consolidates information on the sources of variability in the abundance indices and assesses their impact on the observed trends, and in turn identifies a set of variables affecting Northern Abalone biology and distribution that are recommended for use in standardization of the abundance indices derived from the Northern Abalone Index Site Surveys.

1.1 METHODOLOGICAL CHANGES

The Northern Abalone Index Site Surveys were developed after the commercial fishery first began to rapidly expand, during which time relatively little was known about Northern Abalone populations or biology. In order to address these knowledge gaps, several exploratory Northern Abalone surveys were undertaken beginning in 1976 (Sloan and Breen 1988). After recognizing the need for a consistent survey protocol, a survey methodology geared towards determining Northern Abalone densities was developed and implemented in 1978 (Sloan and Breen 1988). Given the highly aggregated nature of Northern Abalone (Breen and Adkins 1980a), the same sites were repeatedly sampled over time to reduce excess heterogeneity in density estimates, and became the first series of Northern Abalone index sites.

The original methods for the Northern Abalone Index Site Surveys are detailed in Breen (1979), with adjustments noted on a survey-by-survey basis in their respective technical reports (see Table 1). DFO (2016) details the Breen Survey Method, which forms the basis for the Northern Abalone Index Site Surveys. This method involves 16 quadrats (1 m by 1 m) arrayed in 4 transects within a 7 m by 16 m area. Quadrats within a transect are spaced 1 m apart, while transects are 4 m apart. Emergent Northern Abalone, namely those that can be seen without overturning rocks, are measured (shell length in mm) in all quadrats or counted when they cannot be measured. Note that emergent Northern Abalone have also been termed exposed in various publications (e.g., DFO 2016). In the current survey protocol, a subsample of quadrats (quadrat numbers 2, 4, 6 and 8 of the 16) are also searched for cryptic Northern Abalone, by shifting all rocks that can be manoeuvered. Any cryptic Northern Abalone found within those quadrats are also measured (or counted) and recorded as cryptic. In order to maintain consistent detection rates, divers remove obstructive algae from all surveyed quadrats.

Despite an overall focus on data continuity, there have been methodological changes in the Northern Abalone Index Site Surveys over time. For example, not all index sites were sampled in each year. In addition, there have been some differences in field protocols, and data collection has evolved throughout the time series. The continuity of data variables collected in the Northern Abalone Index Site Surveys is summarized in Appendix A, Tables A.1-A.14. We examined three methodological changes that may have impacted observed densities: (1) site location; (2) quadrat count; and (3) cryptic searches.

1.1.1 Index site location

Northern Abalone Index Site Surveys are currently conducted in six regions on a five-year rotation. The regions are East Coast Haida Gwaii (ECHG), West Coast Haida Gwaii (WCHG), Central Coast (CC), Queen Charlotte Strait (QCS), Georgia Basin (GB), and West Coast Vancouver Island (WCVI, Figure 1). When the surveys were first established, only two regions were included: ECHG and CC. Index sites within those regions were selected based upon the presence of strong Northern Abalone populations that were considered harvestable (Breen and Adkins 1981; DFO 2016). The other regions and additional index sites have been progressively added over time, and are now based on random site selection. However, generally only those randomly selected sites which contain Northern Abalone habitat are repeated on subsequent surveys (Atkins and Lessard 2004; Egli and Lessard 2011; Lessard and Egli 2011; DFO 2016).

The addition of new index sites and regions over time represents one source of variability in the Northern Abalone Index Site Surveys dataset. Index sites have also been excluded when habitat became unsuitable or sites became unsurveyable (Curtis and Zhang 2018), for example due to inundation of sites by sand. Occasionally, inclement weather or other hazards can prevent the re-surveying of index sites. Furthermore, the ability to relocate sites has improved over time as advances in the accuracy of GPS technology reduces variability in the positioning of index site locations. Thus, there is discontinuity in index sites surveyed over time and the extent of the time series varies between regions. Given the highly patchy nature of Northern Abalone distribution (Sloan and Breen 1988) and the large within- and between-site variation in abundance, discrepancies in surveyed sites have the potential to impact trends in the time series of Northern Abalone density and are examined further in this report.

1.1.2 Quadrat count

The original Breen Survey Method consists of 16 quadrats, yet in the majority of the Northern Abalone Index Site Surveys, if no Northern Abalone were observed in the first eight quadrats, no further quadrats were surveyed (Breen and Adkins 1979; Curtis and Zhang 2018). In other instances, surveys incorporated multiple adjacent Breen surveys for totals of 32, 48, or 64 quadrats in order to evaluate variance (Campbell 1996). Thus, the number of quadrats sampled is variable, summarized in Table 2. The probability of detecting Northern Abalone presence increases with sampling effort (for example number of quadrats) (Atkins et al. 2004). As such, past practices of assigning a zero density to a site with reduced survey effort may have resulted in underestimates of prevalence and density (Curtis and Zhang 2018). The implications of changes in quadrat number are examined herein, to determine whether a constant number of quadrats sampled is necessary across the time series.

1.1.3 Cryptic Northern Abalone searches

Northern Abalone undergo an ontogenetic shift in habitat use and cryptic behavior that is likely associated with their declining vulnerability to predation with increasing size (Sloan and Breen 1988; Lessard et al. 2007b; Zhang et al. 2007; Griffiths and Gosselin 2008). Mature Northern Abalone ($\geq$ 70 mm) tend to occupy exposed rock surfaces, whereas juveniles ($\geq$ 20 to $<$ 70 mm) are more commonly found in cryptic habitats such as crevices or the undersides of rocks (Sloan and Breen 1988; Cripps and Campbell 1998). Surveys that focus solely on emergent Northern Abalone are therefore likely to disproportionately underestimate juvenile Northern Abalone densities and recruitment. However, this remains a common approach as it reduces the time needed to conduct the survey and results in minimal disturbance to the site. The Northern Abalone Index Site Surveys have gone through several protocol changes with respect to searching for cryptic Northern Abalone, summarized in Table 3. When the survey was first established (1978), only emergent Northern Abalone were counted at most sites (Table 3; Sloan and Breen 1988; Breen and Adkins 1979). Shortly thereafter (1979), searches for cryptic Northern Abalone were included due to low observations of emergent juvenile Northern Abalone relative to the density of adults (Breen and Adkins 1981). By 1994, the survey protocol returned to searching only for emergent Northern Abalone to reduce the survey time (Winther et al. 1995; Campbell 1996). As Sea Otter (*Enhydra lutris*) populations become re-established along parts of the BC coastline, the vulnerability and cryptic behaviours of Northern Abalone appear to be changing (Campbell 1996; Watson 2000; Lee et al. 2016). This shift in Northern Abalone behaviour has once again led to an increased interest in surveying cryptic Northern Abalone (DFO 2016). In order to survey cryptic Northern Abalone without greatly increasing survey time or reducing the number of sites that can be surveyed, the survey protocol changed in 2008 to include subsampling quadrats for cryptic Northern Abalone (Lessard and Egli 2011). Cryptic Northern Abalone searches using the quadrat subsample method have been employed since 2013, with slight variations (Table 3). The influence of the many changes in cryptic versus emergent search protocols are not tested in this report, however they are accounted for by relying upon emergent estimates and applying cryptic correction factors as necessary (Lessard et al. 2007a, see Section 2.1.3).

1.2 ENVIRONMENTAL VARIABILITY

In addition to methodological changes, both abiotic and biotic environmental conditions likely contribute to the variability in the densities measured by the Northern Abalone Index Site Surveys. Northern Abalone distribution and density is influenced by substrate type, wave exposure, depth, salinity (Sloan and Breen 1988; Campbell and Cripps 1998; Cripps and Campbell 1998; Tomascik and Holmes 2003; Lessard et al. 2007b; Lee et al. 2016; Neuman et al. 2018), and the presence and abundance of micro- and macro-algal species (e.g., food sources such as *Macrocystis pyrifera* and *Nereocystis luetkeana* (Lessard et al. 2007b; Lee et al. 2016)), among other variables. Preferred habitat differs between juvenile and adult Northern Abalone (Sloan and Breen 1988; Campbell and Cripps 1998). For example, juvenile Northern Abalone are typically found deeper than adults (Breen and Adkins 1980b; Sloan and Breen 1988; Campbell and Cripps 1998; Cripps and Campbell 1998; Tomascik and Holmes 2003), are more cryptic (Sloan and Breen 1988; Cripps and Campbell 1998; Lessard et al. 2007b; Zhang et al. 2007) and are thought to associate with crustose coralline, articulated coralline, and red branching algae (Sloan and Breen 1988), which may provide a settlement cue (Moss and Tong 1992; Roberts 2003). Earlier studies have also demonstrated the importance of other species in influencing Northern Abalone densities, including predators (e.g., Sea Otter; Watson 2000; Lee et al. 2016), competitors and commensal species (e.g., the Red Sea Urchin, *Mesocentrotus franciscanus*, is a competitor for food and space but may also benefit juvenile Northern Abalone that shelter from predators beneath the spine canopy; Tomascik and Holmes 2003; Rogers-Bennett et al. 2011). Changes in the abundance of Northern Abalone predators, such as large declines in the Sunflower Star (*Pycnopodia helianthoides*) beginning in 2013 (Schultz et al. 2016; Harvell et al. 2019), increases in Sea Otter in some areas (Watson 2000; Nichol et al. 2015), and synergistic effects of these changes (Lee et al. 2016; Burt et al. 2018), may have introduced further variability in Northern Abalone abundance into the index sites time series.

1.3 RESEARCH OBJECTIVES

We focused on three main objectives to test the impact of intrinsic variability and to identify variables to standardize the abundance indices for the Northern Abalone Index Site Surveys (1978-2018). The first objective was to test the sensitivity of the observed density trends to changes in the number of index sites and quadrats sampled over time, and thereby, determine the set of index sites and quadrats to include in further analyses. The second objective was to identify a set of environmental variables that affect Northern Abalone biology and distribution and explore their use in standardizing the abundance indices. The third objective was to analyze the existing survey data and survey design to test the impact of the current level of variability on the detection of differences in the observed density.

2 METHODS

2.1 INDEX SITE DATA

The current version (August 2019) of the DFO Northern Abalone database encompasses data from surveys dating back to 1977 and is managed by the Shellfish Data Unit. It contains data from a variety of survey types, including index sites, plot surveys, timed swims, transects, and tag/recovery surveys. The oldest of these data were recovered from VAX/VMS tapes and field data sheets from the 1970s and 1980s, which were eventually amalgamated into a modern database. This report is the first detailed analysis of the full time series for the Northern Abalone Index Site Surveys (1978-2018) since it was loaded into its current MS SQL Server repository in 2015. To ensure data integrity, a variety of quality assurance and quality control tasks were completed prior to the analyses. The dataset was checked for transcription accuracy by grouping like values, identifying outliers, comparing the outlier database values with original datasheets and applying corrections as necessary. Where values were identified as missing in the database, it was possible in some circumstances to recover the values from original datasheets or publications. Missing tide height corrections for recorded depths were completed for survey years 2012, 2016 and 2017. The dataset was also checked for continuity. Code sets were reviewed and updated as necessary to align with current DFO Pacific regional standard code sets. Values of null and zero were examined and altered as necessary to achieve consistent application in a given database field.

Data from the Northern Abalone Index Site Surveys (1978-2018) were extracted from the Northern Abalone Database in R version 3.6.0 (R Core Development Team 2019) using the RODBC package (Ripley and Lapsley 2017) by selecting survey design code 1 (Breen Survey Method) or survey design code 2 (doubled Breen Survey Method) in the Headers database table. This extraction contained 1926 records at the index site level from 37 surveys across the regions surveyed. Index site data are available from six regions: ECHG, WCHG, CC, QCS, GB, and WCVI (Figure 1). The six regions were grouped into two datasets (Northern BC and Southern BC) because of their similar trends and values for mean observed density over the time series (Figure 2), even though genetic analyses provide no evidence for more than one population in BC (Withler et al. 2003; COSEWIC 2009). The Northern BC group included the ECHG, WCHG, and CC regions, while the Southern BC group included the QCS, GB, and WCVI regions. Johnstone Strait (JS) was surveyed in two locations in 1986 (Adkins 1996) and in 36 locations, alongside the QCS region, in 2004 (Figure 1, Davies et al. 2006). These JS surveys were not included with the QCS region or in the Southern BC dataset as JS contains limited Northern Abalone habitat (Lessard and Egli 2011) and is not currently surveyed as part of the Northern Abalone Index Site Surveys. Removal of the JS surveys left 1888 records at the index site level.

The primary source of total Northern Abalone counts for a given index site or region is the “AbExposed” (counts of emergent Northern Abalone) field in the Density database table. Counts of Northern Abalone that were observed but could not be measured are recorded in a separate field (“AbsNotMeasured”) and were not included in the analyses. The “TD” field (shell length in mm) in the Size Frequency database table was used to obtain Northern Abalone counts sorted by size category. Only counts and size-frequencies of emergent Northern Abalone were used in the analyses in this report.

2.1.1 Density by size category

The extracted shell lengths of emergent Northern Abalone were binned by size into four categories: (1) total Northern Abalone ($\geq$ 20 mm); (2) juvenile Northern Abalone ($\geq$ 20 mm to $<$ 70 mm); (3) adult Northern Abalone ($\geq$ 70 mm); and (4) large Northern Abalone ($\geq$ 100 mm) and summed to get counts. Northern Abalone become sexually mature around 50 mm, with approximately 50% observed to reach sexual maturity at 50 mm (44 to 55 mm depending on location) and 100% at 70 mm (Quayle 1971; Campbell et al. 1992, 2003). Total Northern Abalone counts in our analyses do not include individuals smaller than 20 mm due to changes in diver search behaviour over the time series and reduced detectability of very small Northern Abalone (Curtis and Zhang 2018). Since the quadrat size used was 1 m^2, densities (Abalone/m^2) were calculated by dividing the counts by the number of quadrats sampled at each index site.

2.1.2 Correction for difference between the observed and measured Northern Abalone counts

Although current surveys measure the shell lengths of all emergent Northern Abalone accessible within the quadrat (as well as cryptic Northern Abalone in designated cryptic search quadrats), the number of observed and measured emergent Northern Abalone in early surveys was often not equal. The severity of this discrepancy varied from year-to-year, with ECHG 1978 and CC 1979 having the greatest differences. In the ECHG 1978 survey, divers attempted to record size-frequency data at 51 of 131 total sites (46 of 51 had Northern Abalone present and 108 of 131 used the Breen method, Breen and Adkins 1979), leading to a difference between the counts of observed and measured emergent Northern Abalone of over 1600 individuals. In the CC 1979 survey, at sites where density was deemed too low to survey efficiently with the Breen Survey Method, individuals were collected from the surrounding area in order to obtain size-frequency data comparable with the standard surveys (Breen and Adkins 1981). This led to over 200 more Northern Abalone measurements than observations within the quadrats. The difference in subsequent years was smaller and generally in the range of 10-20 Northern Abalone.

To correct the densities for index sites where the number of emergent Northern Abalone measured did not match the number observed, density for each size category at the index site ($D_{h,i}$) was calculated as:

$$D_{h,i} = \frac{n_{h,i}}{n_i} \cdot D_i \tag{1}$$

where $n_{h,i}$ is the number of Northern Abalone measured in size category h at index site i, n_i is the total number of Northern Abalone measured at the index site and D_i is the total density (Abalone/m^2) at the index site based on the number of Northern Abalone observed in the surveyed quadrats (Lessard et al. 2007a). This correction was applied to only differences between the size-frequency data and the counts of emergent Northern Abalone and did not include counts recorded in the “AbsNotMeasured” field.

2.1.3 Correction for cryptic Northern Abalone included in counts

In 1979, 1980, 1983 and 1985, counts of emergent and cryptic Northern Abalone were not recorded separately. Correction factors of 0.836 for immature ($<$ 70 mm), and 0.991 for mature ($\geq$ 70 mm) and large ($\geq$ 100 mm) Northern Abalone were applied to the data, as per Lessard et al. (2007a). The appropriate correction factors were multiplied by the site-level size-frequency derived densities of the respective juvenile, adult and large adult categories. The size-frequency derived total Northern Abalone category was corrected for these years by summing the corrected densities for the juvenile and adult size categories.

2.1.4 Correction for a change to the quadrat size

The "Comments" field of the Northern Abalone database notes four occasions during the 1979 CC survey when the incorrect quadrat size was used: "quadrat used smaller than 1 m^2 (density $\times$ 1.53)". Based on the densities reported in Table 1 of Breen and Adkins (1981) and the counts of emergent Northern Abalone recorded in the database, densities for three of these index sites (keys 2434, 2436, 2442) were multiplied by 1.53.

2.1.5 Excluded index sites

Due to the varied goals of the Northern Abalone Index Site Surveys over time, it was necessary for certain index sites to be excluded from our analyses for consistency (Table 4). In total, 173 index site records were removed from the time series leaving 1715 index site records for the analyses. Index sites were excluded if they were only surveyed once during exploratory surveys and never returned to, if they were surveyed for non-index purposes (e.g., environmental impact assessments), and if no size-frequency or quadrat-level data were recorded at a given site. These site exclusions differ slightly from the methods in COSEWIC (2009), where 108 index sites were used for total density in 1978 (ECHG), but only 51 index sites could be used for density by size category (see also Table 1). Due to the removal of individuals less than 20 mm from the total density of Northern Abalone, only index sites with size-frequency data were included in our analyses. Retaining only 51 sites for ECHG in 1978 increased the mean total Northern Abalone density slightly from 2.22 $\pm$ 0.24 Abalone/m^2 ($\pm$ s.e.) to 2.52 $\pm$ 0.40 Abalone/m^2. Curtis and Zhang (2018) also excluded some index sites due to poor habitat or poor sampling conditions for surveys between 2000 and 2016. Those index sites are retained in our analyses, as their removal had no discernible effect on overall trends and a consistent method for index site exclusion due to poor habitat or poor sampling conditions had not been developed and applied to the entire time series (1978-2018).

Following these method-based exclusions, there were two years with very few data points in Southern BC (one year with only two index sites and one year with only 12 index sites). The year with only two index sites (1982, GB region) was removed from all subsequent analyses leaving 1713 index site records for analysis. Additionally, the one year with only 12 index sites (1985, GB region) was removed from the analyses identifying environmental covariates (1701 index site records remaining).

2.1.6 Sensitivity test for index site continuity

Relatively few index sites were sampled every year that Northern Abalone surveys were conducted in a given region (Figure 3). We assessed the sensitivity of observed Northern Abalone densities to sampling different index sites and locations over the time series. Densities were calculated for the full complement of index sites, as well as for a restricted series of index sites. The original intention was for the restricted series to include only those index sites which had been sampled during every survey in a region. However, in the two regions with the longest time series this resulted in a sample size (number of sites) that was too small ($n \leq 1$ in CC and ECHG). A looser set of criteria was therefore established. The restricted series of index sites was selected based on the number of times index sites were revisited during regional surveys, summarized in Figure 3. In order to compare the trends in the full and restricted series, we scaled each series by dividing the annual mean observed Northern Abalone densities by the geometric mean of the series, using methods similar to those in Anderson et al. (In press). For each year in the time series, we then took the ratio of the scaled mean total Northern Abalone density (full series, shell length $\geq$ 20 mm) divided by the scaled mean total Northern Abalone density (restricted series) and subtracted it from one. T-tests were used to determine whether these ratios differed significantly from zero (i.e. whether the trends in the full and restricted series were the same), for the Northern BC dataset and the Southern BC dataset separately. All t-tests were conducted in R version 3.6.0 (R Core Development Team 2019).

2.1.7 Sensitivity test for number of surveyed quadrats

Although the Breen Survey Method includes 16 quadrats arrayed in a specific pattern (described in Section 1.1.2), the surveys conducted throughout the time series occasionally deviated from this standard design. For example, in certain years when no Northern Abalone were observed in the first eight quadrats at a site, the survey at that site was prematurely truncated. There are accordingly a few site surveys consisting of only eight quadrats. This occurred in 11% of cases (190 of 1713 index site records). A list of these discrepancies, based on survey plans and summaries, as well as the data, are presented in Table 2. Sensitivity tests were used in order to test the implications of the decision to truncate site surveys when no Northern Abalone were observed in the first eight quadrats.

Sensitivity tests involved first truncating all surveys in the time series for which no Northern Abalone were observed in the first eight quadrats, by simply excluding the data from the last eight quadrats in those cases. Approximately 24% of site surveys (409 of 1713 index site records) had zero counts for the first eight quadrats. Of these, 54% (221 index site records) consisted of greater than eight quadrats. Total Northern Abalone (shell length $\geq$ 20 mm) densities derived from the newly truncated data were then compared to total Northern Abalone densities calculated based on the full dataset. T-tests were used to test whether the ratio (subtracted from one) of the scaled mean total Northern Abalone densities between the full and quadrat-truncated datasets was significantly different from zero, as with the sensitivity test for index site continuity (Section 2.1.6). The t-tests were performed on the Northern BC and Southern BC datasets separately and densities were scaled by their respective geometric means, in R version 3.6.0 (R Core Development Team 2019).

2.2 IDENTIFYING POTENTIAL ENVIRONMENTAL VARIABLES FOR STANDARDIZING THE INDEX SITE SURVEYS TIME SERIES

2.2.1 Environmental variables collected at the time of the survey

In addition to Northern Abalone density, the index site data extracted from the Northern Abalone database also contained site-level and quadrat-level environmental variables collected at the time of the survey (Appendix A, Table A.1). These are stored in the Headers, Site Descriptions and Density database tables (Appendix A, Table A.1) and include tide-corrected depth, temperature measured at the site and exposure (estimated in categories). A calculated exposure (Lessard and Campbell 2007) was also included in the data, but is only available for the years 1978-1980. An estimated slope (based on diver estimates in 10 degree slope bins) was also available for a number of sites. The diver-collected depth and diver-estimated exposure variables were only populated for approximately half of the index sites. None of the environmental variables collected at the time of the survey were consistently measured over the entire dataset or time series (see Appendix A, Tables A.2-A.14).

2.2.2 Northern Abalone predators

In addition to the environmental variables measured at the index sites, two indicators of predation pressure were also incorporated into the site-level data. The first was the abundance of sunflower stars, which has been recorded at the quadrat-level since 2006. These counts were turned into density estimates using the quadrat size and added to the data by matching the unique site key (variable name *Pycnopodia*, Table 5). The second index of predation was the occupancy of sea otters at each index site (Table 5).

2.2.3 Sea Otter occupancy at the index sites

Sea otters are recolonizing parts of their former range in BC, and Sea Otter rafts have been observed in parts of the WCVI, CC and QCS regions (Nichol et al. 2015). For these three regions, index sites in locations that overlap with the recent distribution of Sea Otter in BC were evaluated for the presence/absence of Sea Otter rafts (three or more individuals) and for the length of Sea Otter occupation. Index sites in all other regions (i.e. ECHG, WCHG, GB) were assigned a code corresponding to absence for Sea Otter occupancy. Sea Otter surveys are not conducted in these regions (Nichol et al. 2015). A GIS-derived index of Sea Otter occupation for Northern Abalone index sites was developed using Sea Otter survey data since 2001. Sea Otter raft locations obtained during spring/summer Sea Otter surveys conducted since 2001 (Nichol et al. 2015) were imported as a shape file into ArcMap 10.1.1. Buffers representing a 3 nautical mile (nm) radius were created around each raft site. If a Northern Abalone index site fell within the buffer, that index site was considered occupied in the year of that survey. As another check, the Northern Abalone index sites were buffered with a 3 nm radius and the raft sightings that intersected with these buffers were identified and the corresponding survey years recorded. Sea Otter rafts tend to form in the same locations over multiple years (Garshelis and Garshelis 1984; Jameson 1989; Nichol et al. 2015), so the presence of a Sea Otter raft in the spring or summer of one year is a strong indication that sea otters will be present in subsequent years (Nichol et al. 2015). Raft sightings at other times of the year (e.g., winter) in a previously unoccupied area are not a reliable indicator of consistent occupation. As the surveys are conducted in spring/summer, every year after the first year of occupation of the Northern Abalone index site (intersection with 3 nm buffer) was considered to be continuously occupied by at least three sea otters.

Two variables were produced based on the first year of Sea Otter occupation at the index sites: (1) presence/absence; and (2) total number of years occupied. For the presence/absence variable, sea otters were recorded as present at the index site for every year of the Northern Abalone Index Site Surveys after the first year of Sea Otter occupation. For the total number of years of occupation variable, the number of calendar years since the first year in which a raft was present at the index site was recorded for each subsequent year of the Northern Abalone Index Site Survey at that site. Note that this type of data is only available as of 2001.

Alternative Sea Otter occupancy variables were produced for the index sites in the WCVI and QCS regions based on the application of expert opinion. On WCVI, Sea Otter surveys started well before 2001, but did not geo-reference the approximate location of all sea otters observed on surveys, therefore the GIS-derived method did not readily apply (Nichol et al. 2015). There has been substantial consistency among years with respect to the Sea Otter survey team on WCVI and thus use of expert opinion to determine when sea otters were first observed within the corresponding 3 nm buffer vicinity of the Northern Abalone index sites was deemed an appropriate approach. In addition, for Northern Abalone index sites that were close to early Sea Otter surveys but not within the 3 nm buffers, expert opinion was used to determine whether the occupation date of the nearest Northern Abalone index site could be used.

For the QCS region, the area over which the Northern Abalone index sites are distributed is relatively small compared to other regions and the sites are quite close together, often less than 2 nm apart. Application of the GIS-derived method resulted in different sea otter presence/absence values for sites that were in close proximity to one another and this seemed biologically unrealistic. Thus, given the time-scale resolution of the Sea Otter survey data, the clusters of Northern Abalone index sites and the motility and foraging behaviour of sea otters, it was assumed that index sites in close proximity would be more likely to have experienced similar foraging pressure from sea otters. Therefore, based on expert opinion, an alternative estimate that assumes these clusters of index sites have been occupied for the same amount of time was used.

2.2.4 GPS locations of the index sites

Positional data (longitude-latitude pairs) for the index sites can be used to derive additional environmental variables (e.g., Regional Ocean Model Systems (ROMS) model outputs). Of the 1926 extracted index site records, n = 341 had no position data. For the remaining 1585 index sites, positional accuracy of the data was an issue, especially in the early years of the Index Site Surveys where accurate GPS positions were not available. Most depths recorded in the field were between 1.5 m and 4 m. The position data placed 445 of the 1585 index sites on land. In addition, two points had latitude and longitude pairs that fell on depths deeper than 30 m. For all these points (n = 447), a corrected position was estimated as the closest position to the recorded latitude-longitude pair that fell within a 0 to 30 m depth band. All corrected depths were within 2 km of the originally recorded point.

2.2.5 Environmental variables from other sources

In addition to the variables collected at the time of the survey (tide-corrected depth, calculated slope, estimated exposure, calculated exposure, and *Pycnopodia* abundance; Table 5), a number of variables thought to be important for Northern Abalone biology and ecology were available on a larger (coast-wide) scale from other studies. The Marine Spatial Ecology and Analysis Section (MSEA; DFO Pacific Region, Science Branch) has been developing GIS coverages based on bathymetry and other layers (Davies et al. In press; Nephin et al. In press) to create habitat suitability models for a wide range of species, including Northern Abalone (Nephin et al. In press). For this analysis, seven variables were derived from compiled seafloor bathymetry (Davies et al. In press) at the Northern Abalone index sites. Bathymetry was available on a 20 m by 20 m grid scale. The derived variables included depth (Bathy), Slope and Aspect (direction the slope was facing). Additionally, three measures of seafloor rugosity were calculated: (1) seafloor roughness; (2) terrain ruggedness index (TRI); and (3) vector ruggedness (VRM; Sappington 2007). Seafloor roughness was calculated as the difference between the maximum and minimum depths of a cell and its eight surrounding cells. TRI was calculated as the mean of the absolute differences between the value of a cell and the values of eight surrounding cells. VRM was calculated according to the methods of Sappington (2007) and is similar to TRI, but also accounts for differences related to the local slope of the seafloor. The final terrain variable calculated was the topographic position index (TPI; the difference between the value of a cell and the mean value of the eight surrounding cells), which indicates whether the site was on a "hill" or in a "valley" relative to its surroundings. All terrain indices were calculated using the raster package in R (Hijmans 2019; R Core Development Team 2019) and are shown in Table 5.

Long-term (1998-2007) spatial patterns in oceanographic variables were also available from ROMS model outputs (Masson and Fine 2012). These included mean summer temperature and salinity predicted for the near-bottom layer (Table 5). It also included average summer current speed and average summer tidal speed predicted by the ROMS model. These variables were averaged for the years 1998-2007 (Nephin et al. In press). The original ROMS models were run for a 3 km grid covering the entire BC coast and were interpolated to a 20 m x 20 m grid for these analyses.

A final variable available on a large scale was predictions from a substrate model (Gregr and Haggarty 2016) for the BC coast to depths of 200 m. The substrate model predicted substrate as a number from 1-4 indicating categories of mud, sand, mixed, and rock. The underlying substrate prediction for each site was extracted using the raster package in R (Hijmans 2019). The 20 m x 20 m gridded raster was used for these analyses.

Exposure of each site has been shown to have a significant impact on Northern Abalone densities in other studies (Lessard and Campbell 2007; Lee et al. 2016). Exposure was calculated by Lessard and Campbell (2007) for three years (1978-1980). To estimate exposure for the additional index sites, we used the waver package in R (Marchand and Gill 2018). The waver package takes the bearings from a point (in this case each index site location) and estimates the distance to land in a specified set of directions. We used directions from 0-330 in 30° increments and summed the distance to land for all these directions as an index of exposure.

The sum of the distances was distinguished from other exposure measures (estimates collected by divers) by naming this variable "Fetch". The Fetch variable was calculated by first making a shoreline from a contour of the bathymetry layer (contour at depth = 0). Then for each index site a Fetch was calculated at 30 degree increments around a circle (i.e. 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 degrees) and summed for the site.

2.2.6 Correlation among the environmental variables

The full matrix of raster-based environmental variables (n = 21, Table 5) was examined across the dataset for multicollinearity through pairs plots (not shown), computing a correlation matrix, and estimating variance inflation factors (VIFs, Zuur et al. 2009, Table 6). It was clear that three of the bathymetry-derived variables (slope, TRI, and roughness) contained essentially the same information (r's $\geq$ 0.95). Thus, slope and roughness were removed from further analysis. In addition, it was clear that salinity and temperature were highly negatively correlated (r = -0.81). Salinity was retained for further analysis. It should be noted that in the results the independent effects of these correlated variables are difficult to disentangle. After removal of these three variables, VIFs were less than two and correlations were generally low across the 10 remaining variables. Plots of pairs of variables also showed that multicollinearity and outliers were minimized.

Next the potential variables collected at the time of the survey (tide-corrected depth, calculated slope, estimated exposure, calculated exposure, and Sea Otter and *Pycnopodia* predator abundance, Table 5) were added to the dataset. Only the presence/absence variables for Sea Otter occupancy (with and without expert opinion) were included, as the number of years of occupancy was correlated with the survey year variable. Sites with no positional data were included at this point as well. Most of these data records were incomplete (one or more variables were not collected). These additional variables were examined for correlations with the raster variables and amongst each other (Figure 4).

The two sets of presence/absence measures of Sea Otter occupancy were highly correlated (r = 0.92), so only the Sea Otter occupation from expert opinion was used in the following analysis. Slope observations and Sea Otter observations did not overlap in the dataset. The *Pycnopodia* measurements also did not overlap with the exposure measurements. The two measures of exposure (exposure calculated by Lessard and Campbell (2007) and exposure estimated at sites) did not overlap over time. VIFs could not be calculated due to the large number of missing data points.

With the exception of the two Sea Otter occupancy (presence/absence) variables, nothing was highly correlated in this dataset. The missing data are problematic. One noticeable result is that depth from the 20 m raster (Bathy) is not correlated to the tide-corrected depth measured by divers (r = 0.14). Exposure calculated from the 1978-1980 data (Lessard and Campbell 2007) and the Fetch variable calculated from raster layers were moderately correlated (r = 0.62). Based on the examination of correlations among the environmental variables, all variables could be included in the following models without violating assumptions of independence (Table 6). Since most of the records are incomplete, not all variables can be evaluated together, so some caution is exercised in considering the results.

2.2.7 Modelling

Modelling of Northern Abalone density was conducted using generalized additive modelling (GAM) implemented in the mgcv package in R (Wood 2006). The analyses tested for significant linear or non-linear effects of environmental variables on Northern Abalone density. The GAM was implemented with a maximum of k = 3 knots for continuous covariates to minimize overfitting. Parametric (factor) terms were also included for categorical variables. In all models, a year term was included as a factor. This year term was included in all models to capture the annual changes in density. The year term is a combination of the effect of year and the effect of region that is not accounted for by the environmental variables, as only one region was surveyed in most years, for the Northern BC and Southern BC datasets (Table 1).

Two analyses of Northern Abalone densities were conducted. First, the entire time series (1978-2018) was analyzed. For the entire time series we fit a full GAM model with all variables available for the duration of the time series (Bathy, TRI, TPI, VRM, Aspect, Fetch, Substrate, Tides, Currents, Salinity and Sea Otter occupancy (presence/absence)). The full model for the entire time series was:

$$\begin{aligned} density_j = \beta_j + s(Substrate_j) + s(Tides_j) + s(Currents_j) + s(Salinity_j) + s(VRM_j) + \\ s(Bathy_j) + s(TPI_j) + s(TRI_j) + s(Aspect_j) + s(Fetch_j) + OtterPA_j + Year_j + \epsilon \end{aligned} \quad (2)$$

where *s* indicates a thin-plate regression spline smoothing function (Wood 2006), β is an intercept, ϵ are Tweedie-distributed errors (Tweedie 1984), and *j* represents either the Northern BC or Southern BC dataset. The Tweedie distribution was used because of the large amount of zero-inflation in the data. The distribution uses a power parameter (*p*) indicating the relationship between the variance (σ^2) and the mean (μ):

$$\sigma^2(y_j) = \phi\mu_j^p \quad (3)$$

where ϕ is the positive dispersion parameter. The power parameter was restricted to a range of 1 to 2 since the data were best represented as a compound Poisson distribution with non-negative values and zero-inflation. The power parameter was estimated simultaneously during model fitting using the mgcv package and with a log-link (Wood 2006).

The second analysis utilized only the later portion of the data set (2006-2018) and here we incorporated the additional variables collected mainly during this time period (*Pycnopodia* abundance, depth, and Sea Otter occupancy (presence/absence)). The full model for the reduced time series was:

$$density_j = \beta_j + [bestmodel_j] + s(Depth_j) + s(Pycnopodia_j) + Year_j + \epsilon \quad (4)$$

where the *bestmodel* is the reduced (best-fitting) model for the entire time series derived above.

Each full model was reduced by stepwise removal of insignificant terms until only significant terms remained (judged by having an approximate p-value $<$ 0.05). Because the mgcv package generates only approximate p-values, the model Akaike information criterion (AIC) or generalized cross-validation parameter (GCV) in combination with parameter estimates and p-values are often used to determine terms that can be removed from the model (Wood and Augustin 2002;

Weinberg and Kotwicki 2008). However, in this case the missing values for many variables in the complete dataset could not be used in the GAM analysis. For example, diver-estimated depths were recorded at only a subset of index sites (1068 of the 1926). Thus, when the diver-estimated depth term was found to be insignificant and removed from the model, additional records with full coverage over the remaining variables became available and could be used to fit the reduced model. In this case, the AIC and GCV were not comparable from the full model to the reduced model, as the dataset had expanded. Since there were no complete cases for all variables in the dataset, use of the approximate p-value was a trade-off between maximizing the data available for the analysis and having a non-standard method of determining term significance.

When the best-fitting model was determined for each time period, model diagnostics were checked for violations of assumptions (e.g., residual plots were checked for adherence to normality and are shown in Appendix B, and optimization diagnostics and model convergence statistics were reviewed to ensure that convergence was achieved). The response curves for Northern Abalone density and the significant environmental variables were plotted and model fits evaluated. To evaluate the impact of including the significant environmental variables on the index of Northern Abalone abundance, a standardized index of Northern Abalone abundance was calculated. To calculate a standardized index, the density for each year was predicted from the best-fitting model by holding the other model variables at their median values. Variation around this prediction was calculated using a bootstrap of 1000 replicate fits and predictions of the best-fitting model (Efron and Tibshirani 1993).

Finally, the effect of the year term was examined for the best model by removing the year term, refitting the model and computing the difference in deviance explained from the best-fitting model and the best-fitting model without a year effect. Each of these analyses were completed on the four size categories of Northern Abalone for both the Northern BC dataset and Southern BC dataset of grouped index sites.

2.3 ANALYSIS OF EXISTING SURVEY DATA AND DESIGN

The third overarching objective of this report, to analyze the existing survey data and survey design to test the impact of the current level of variability on the detection of differences in observed density, can be further broken down into three steps: (1) to estimate the coefficient of variation on the existing index survey by region (i.e. ECHG, CC, WCVI, QCS, GB, WCHG) under various sample sizes; (2) to estimate the detectible difference in Northern Abalone density that could be obtained using historical sampling data; and (3) to determine the effect of adding quadrats and/or sites on the precision of density estimates for Northern Abalone.

The first analyses examined the historical sample sizes of the Northern Abalone Index Site Surveys and resulting estimates of mean density and variance. The density at both the quadrat- and site-level was examined for the Northern BC and Southern BC datasets. These were the same datasets used in the index modelling, although only the total Northern Abalone size category ($\geq$ 20 mm shell length) were analyzed. The mean, variance and coefficient of variation within and among sites were calculated. Additionally, using the observed standard deviation, sample size versus coefficient of variation curves were estimated at sample sizes of three to 200 for quadrats and three to 1000 for sites. All calculations were performed in R version 3.6.0 (R Core Development Team 2019) using the formulae of Thompson (1992) and Gunderson (1993).

The second step was to estimate the minimum detectable difference in total Northern Abalone density ($\geq$ 20 mm shell length) for a range of sample sizes and the average historical sample size from each area. The difference was compared to the observed density to determine the size of difference in Northern Abalone abundance that could be detected using the existing survey methodology. To estimate the minimum detectable difference we used the equation of Cohen (1988), where the effect size *d* was estimated by:

$$d = \frac{(\mu_1 - \mu_2)}{\sigma} \tag{5}$$

where μ_1 and μ_2 are the mean density from year 1 and year 2, respectively, and σ is the pooled standard deviation. Power was set to 0.9 and α to 0.05 (Cohen 1988; Champley 2018).

As a final exercise, a resampling experiment was set up to simulate where the greatest gain in precision could be attained, either by increasing the number of quadrats or the number of sites sampled during the surveys. For this exercise we used bootstrapping to resample the data with quadrat numbers from 2 to 64 per site and the number of sites from 3 to 200 for each region in the Northern BC and Southern BC datasets. Resampling was done across regions, and years and sites were pooled. The simulation resampled the index site data for both quadrats and sites simultaneously so that the net benefit to increasing the number of each could be gauged. This analysis was conducted using the two-stage sampling design (site and quadrat) of Szarzi et al. (1995), so that a combined variance could be estimated from the two stages for the index sites.

3 RESULTS

3.1 SENSITIVITY TESTS

3.1.1 Index site continuity

Site selection did not appear to impact observed mean total Northern Abalone ($\geq$ 20 mm shell length) densities for the Northern BC or Southern BC datasets. Densities were comparable between the full and restricted series for all the index sites combined (Figure 5), and for the Northern BC and Southern BC datasets (Figure 6). Greatest impacts occurred in the early years of the Northern Abalone Index Site Surveys in Northern BC, as is apparent from a visual and graphical assessment of densities calculated from size-frequency data (Figure 6). Interestingly, the restricted series trendline declines before that of the full series, suggesting that inclusion of new sites in the first three years of the time series may have delayed detection of declining total Northern Abalone densities in Northern BC. However, this detection would have been limited by small sample size and large error terms in the restricted series. The mean of the difference in density between the full and restricted series was 0.020 abalone/m^2 for the Northern BC dataset and -0.028 abalone/m^2 for the Southern BC dataset (total Northern Abalone category of individuals $\geq$ 20 mm shell length). There was no significant difference in scaled annual mean total Northern Abalone densities of the full and restricted series, for the Northern BC dataset ($t = -0.578$, $df = 23$, p-value = 0.569), but there was a significant difference for the Southern BC dataset ($t = -2.871$, $df = 6$, p-value = 0.028). The statistically significant difference was likely due to the small sample size in Southern BC ($n = 7$). Analyses conducted in this report are based upon the full series of index sites, with a few site exclusions due to other criteria (see Section 2.1.5), as the overall trends in the full and restricted series were similar, and the restricted series had a smaller sample size and increased variability. Nevertheless, it is important to bear in mind the possible implications of including all index sites when interpreting trends in mean total Northern Abalone densities over time (e.g., delayed decline).

3.1.2 Number of surveyed quadrats

Quadrat truncation did not have a statistically significant impact on the scaled mean total Northern Abalone ($\geq$ 20 mm shell length) densities by year for the Northern BC dataset (t = -0.084, df = 23, p-value = 0.934) or the Southern BC dataset (t = -0.058, df = 8, p-value = 0.955). The mean of the difference in density between the two methods was only 0.010 abalone/m^2 for the Northern BC dataset and 0.003 abalone/m^2 for the Southern BC dataset, with the full complement of quadrats having on average higher densities. Visual and graphical assessment of the densities calculated from size-frequency data further emphasizes that Northern Abalone density trends over the time series are similar irrespective of truncation of quadrat number when no Northern Abalone are present in the first eight quadrats for both the combined data (Figure 7) and the Northern BC and Southern BC datasets (Figure 8).

3.2 IDENTIFYING ENVIRONMENTAL VARIABLES FOR STANDARDIZING THE INDEX SITES - NORTHERN BC DATASET (ECHG, CC, WCHG REGIONS)

3.2.1 Total Northern Abalone ($\geq$ 20 mm shell length)

For the total Northern Abalone ($\geq$ 20 mm) size category, the raw data indicated that there were non-linear relationships between density and Substrate, Fetch, and Salinity (Appendix B, Figure B.1). For most variables there was a reasonably even coverage of density observations across the range of variables. For tidal currents (Tides) there were two outlier observations at extreme tides.

The reduced model contained only four significant variables, Salinity, VRM, TRI and Fetch, plus the year term that reflected annual (and regional) changes in abundance not accounted for by the other variables (Table 7). Northern Abalone density increased with increasing Salinity, increasing Fetch, and increasing VRM, and had a dome-shaped relationship with TRI (Figure 9). The model's explanatory power was reasonable, as it explained about 43.8% of the deviance in the Northern Abalone densities over the entire time series (Table 7). Residuals were generally consistent with normality (Appendix B, Figure B.2) and the Tweedie power parameter was 1.49. The year term explained most of the variability in the dataset. When the year term was removed, the deviance explained dropped to only 3.7%. Thus, year explained 91.5% of the deviance in the model.

When only the data from 2006-2018 were analyzed, neither the variables collected at the time of the survey (Depth and *Pycnopodia* density) nor Fetch nor VRM were significant, resulting in a best-fitting density model with only Salinity and TRI (Table 7). The relationships were consistent with the analysis containing pre-2006 data (Figure 9), with increases in Northern Abalone density with increased Salinity and TRI (Figure 9). Model diagnostics were reasonable with a Tweedie power parameter of 1.39 (Appendix B, Figure B.3). The model explained 22.7% of the deviance when the year term was included (Table 7) and only 5.4% of the deviance when the year term was excluded. The year term explained 76.4% of the variability in the model.

3.2.2 Juvenile Northern Abalone ($\geq$ 20 mm and $<$ 70 mm shell length)

For juvenile Northern Abalone ($\geq$ 20 mm and $<$ 70 mm shell length), the raw data indicated that there were potential non-linear relationships between density and VRM, Bathy, and TPI (Appendix B, Figure B.4). Linear relationships were apparent between density and Fetch, and density and Salinity. For most variables there was a reasonably even coverage of density observations across the range of variables.

The best-fitting model of juvenile Northern Abalone density included six significant variables (Table 7). As with the previous analysis, density increased with increasing Salinity, increasing Fetch and had a dome-shaped relationship with TRI (Figure 9). The model also indicated that substrate type (Substrate) was significantly correlated to Northern Abalone density, with juvenile Northern Abalone density increasing with decreasing Substrate index (generally less rocky habitat). Juvenile Northern Abalone density decreased with increasing tidal currents (Tides) and increased with increasing habitat ruggedness (VRM). The model explained 49.7% of the deviance in the data when the year term was included (Table 7) and only 10.7% when the year term was excluded, indicating 78.4% of the variance was explained by the year term. Model diagnostics indicated the Tweedie power parameter of 1.48 resulted in a reasonable model fit (Appendix B, Figure B.5).

For juvenile Northern Abalone during 2006-2018, only five variables that were significant for the full time series were included in the best-fitting model (Table 7). The relationships between juvenile Northern Abalone density and significant variables (Tides, Salinity, Fetch, Substrate and VRM) were the same for the 2006-2018 data as for the full time series (Figure 9). The Tweedie power parameter was 1.4, and the model diagnostics showed reasonable fits to the residuals (Appendix B, Figure B.6). The best-fitting model explained 34.9% of the deviance with the year term included (Table 7) and only 15.8% of the deviation when the year term was removed, indicating the year term explained about 54.6% of the variability explained by the model.

3.2.3 Adult Northern Abalone ($\geq$ 70 mm shell length)

For adult Northern Abalone ($\geq$ 70 mm shell length), the raw data indicated that there were non-linear relationships between density and Substrate, and potential linear reationships with TPI, bathymetry (Bathy), and Salinity (Appendix B, Figure B.7). For most variables there was a reasonably even coverage of density observations across the range of variables.

The best-fitting model of adult Northern Abalone density included five significant covariates (Table 7). As with the previous analysis, adult Northern Abalone density increased with increasing Salinity (although nonlinearly). Adult Northern Abalone density increased linearly with increasing depth (Bathy) (Figure 9). Adult Northern Abalone density also increased with increasing tidal currents (Tides) and decreased with increasing Fetch, in contrast to the juvenile model (Figure 9). Sea Otter presence had a negative effect on the density of adult Northern Abalone. The model explained 32.8% of the deviance in the data when the year term was included (Table 7) and only 3.8% when the year term was excluded, indicating 88.3% of the variance was explained by the year term. Model diagnostics indicated the Tweedie power parameter of 1.46 resulted in a reasonable model fit (Appendix B, Figure B.8).

When only the 2006-2018 adult Northern Abalone density was analyzed, the best-fitting model was simpler, containing only Salinity as a covariate (Table 7). Consistent with the other analyses, density increased with increasing Salinity (Figure 9). Model diagnostics indicated the Tweedie power parameter of 1.42 resulted in a reasonable model fit (Appendix B, Figure B.9). The model explained 15.8% of the deviance in the data when the year term was included (Table 7), and when the year term was excluded the model became insignificant, indicating that the year term was explaining 98.2% of the model results for adult Northern Abalone.

3.2.4 Large adult Northern Abalone ($\geq$ 100 mm shell length)

For large adult Northern Abalone ($\geq$ 100 mm shell length), the raw data indicated that there were potential non-linear relationships between density and Salinity, tidal currents (Tides), and TPI (Appendix B, Figure B.10). For most variables there was a reasonably even coverage of density observations across the range of variables.

The best-fitting model of large adult Northern Abalone density included five significant covariates (Table 7). As with the adult analysis, large adult Northern Abalone density increased with increasing tidal currents (Tides; Figure 9). In the model of large adult Northern Abalone density, density decreased with increasing Salinity to about 32 ppt and then increased as salinities became higher (Figure 9). Large adult Northern Abalone densities also increased linearly with increasing TPI and decreased with increasing VRM and Fetch (Figure 9). The model explained 34.8% of the deviance in the data when the year term was included (Table 7) and only 8.3% when the year term was excluded, indicating 76.1% of the variance was explained by the year term. The Tweedie power parameter was 1.32. The model diagnostics indicated that there were some slight deviations in the residuals (particularly indicated by the quantile-quantile normal plot, Appendix B, Figure B.11).

When only the 2006-2018 large adult Northern Abalone density was analyzed, the best-fitting model explained 17.9% of the deviance (Table 7). Like the previous models, Salinity and tidal currents (Tides) were significant (Table 7). Large adult Northern Abalone densities increased with increasing Salinity and increasing tidal currents (Tides; Figure 9). For the first time, one of the variables collected at the time of the survey (Depth) occurred as a significant covariate in the model. Large adult Northern Abalone density decreased linearly with increasing depth at the site (Figure 9). Model diagnostics were reasonable (Appendix B, Figure B.12), and the Tweedie power parameter was estimated at 1.29. When the year term was excluded, the model explained only 4% of the deviance, indicating that about 77.6% of the variability in the dataset was explained by the year term.

3.2.5 Evaluating the environmental variables in a standardized index of abundance

To estimate a standardized index of abundance for each size category of Northern Abalone, the best-fitting GAM was used to predict the density of Northern Abalone in each year by holding the other variables in the model at their mean value. The results show that index standardization using GAM did not affect the resulting patterns in Northern Abalone abundance at the index sites (Figure 10). In general, the variability was about the same between standardized and non-standardized estimates and the trends in abundance were roughly the same across size categories. The large and variable effect of the year term (year effect and region effect not accounted for by the environmental variables) in all of the models and the relatively small explanatory power of environmental variables in the absence of the year term, across all datasets, explains this lack of improvement in the standardized Northern Abalone abundance index.

3.3 IDENTIFYING ENVIRONMENTAL VARIABLES FOR STANDARDIZING THE INDEX SITES - SOUTHERN BC DATASET (WCVI, QCS, GB REGIONS)

3.3.1 Total Northern Abalone ($\geq$ 20 mm shell length)

For the total Northern Abalone size category ($\geq$ 20 mm shell length), the raw data indicated that there were non-linear relationships between density and Substrate, and Fetch (Appendix B, Figure B.13). For most variables there was a reasonably even coverage of density observations across the range of variables.

The reduced model contained two significant variables, current speed (Currents) and the presence/absence of sea otters (Table 7). Northern Abalone density had a dome-shaped relationship with current speed (Currents; Figure 11) and the abundance of Northern Abalone was higher where sea otters were present. The model explained about 25.3% of the deviance in the Northern Abalone densities over the entire time series (Table 7). Residuals were generally consistent with normality (Appendix B, Figure B.14) and the Tweedie power parameter was 1.26. The year term explained most of the variability in the dataset. When the year term was removed, the deviance explained dropped to only 10.4% of the deviance. Thus, the year term explained 59.1% of the deviance in the model.

When only the index site data from 2006-2018 were analyzed, the reduced model contained four significant variables: current speed, depth, *Pycnopodia* density and the presence/absence of sea otters (Table 7). Northern Abalone density increased with increasing current speed (Currents), and was slightly dome-shaped for Depth (Figure 11). The abundance of Northern Abalone was higher where sea otters were present. Northern Abalone density decreased with increasing *Pycnopodia* density (Figure 11). Model diagnostics were reasonable with a Tweedie power parameter of 1.19 (Appendix B, Figure B.15). The model explained 25.4% of deviance when the year term was included (Table 7) and only 22.4% of deviance when the year term was excluded. The year term explained 11.8% of the variability in the model.

3.3.2 Juvenile Northern Abalone ($\geq$ 20 mm and $<$ 70 mm shell length)

For juvenile Northern Abalone ($\geq$ 20 mm and $<$ 70 mm shell length), the raw data indicated that there were potential non-linear relationships between density and VRM, Bathy, and TPI (Appendix B, Figure B.16). Linear relationships were apparent between density and Fetch, and Salinity. For most variables there was a reasonably even coverage of density observations across the range of variables.

The best-fitting model of juvenile Northern Abalone density included three significant variables (Table 7). As with the previous analysis, density had a dome-shaped relationship with current speed (Currents) and bathymetry (Bathy; Figure 11). Density also increased with increasing Aspect (northward facing shoreline) (Figure 11). The model explained 30.2% of the deviance in the data when the year term was included (Table 7) and only 9.1% when the year term was excluded, indicating 69.9% of the variance was explained by the year term. Model diagnostics indicated the Tweedie power parameter of 1.25 resulted in a reasonable model fit (Appendix B, Figure B.17).

For juvenile Northern Abalone during 2006-2018, the best-fitting model contained current speed (Currents), Depth, and Sea Otter presence/absence (Table 7). Juvenile Northern Abalone density increased with current speed and depth (Figure 11). Density of juvenile Northern Abalone was also higher at sites with sea otters present. The Tweedie power parameter was 1.18, and the model diagnostics showed reasonable fits to the residuals (Appendix B, Figure B.18). The best-fitting model explained 26.1% of the deviance with the year term included (Table 7) and only 14.9% when the year term was removed, indicating the year term explained about 42.8% of the variability explained by the model.

3.3.3 Adult Northern Abalone ($\geq$ 70 mm shell length)

For adult Northern Abalone ($\geq$ 70 mm shell length), the raw data indicated that there were non-linear relationships between density and Substrate, and potential linear relationships with TPI and bathymetry (Bathy) (Appendix B, Figure B.19). For most variables there was a reasonably even coverage of density observations across the range of variables.

The best-fitting model of adult Northern Abalone density included only the presence/absence of sea otters (Table 7). Adult Northern Abalone density was higher at sites where sea otters were present (Figure 11). The model explained 22.6% of the deviance in the data when the year term was included (Table 7) and only 9% when the year term was excluded, indicating 60.2% of the variance was explained by the year term. Model diagnostics indicated the Tweedie power parameter of 1.12 resulted in a reasonable model fit (Appendix B, Figure B.20).

When only the 2006-2018 adult Northern Abalone density was analyzed, the best-fitting model included a linear decrease in Northern Abalone density with increasing *Pycnopodia* density (Table 7, Figure 11). Model diagnostics indicated the Tweedie power parameter of 1.15 resulted in a reasonable model fit (Appendix B, Figure B.21). The model explained 15.6% of the deviance in the data when the year term was included and when the year term was excluded the model became insignificant indicating that the year term was explaining 41.2% of the model results for adult Northern Abalone.

3.3.4 Large adult Northern Abalone ($\geq$ 100 mm shell length)

For large adult Northern Abalone ($\geq$ 100 mm shell length), the raw data indicated that there were potential non-linear relationships between density and tidal currents (Tides), and TPI (Appendix B, Figure B.22). For most variables there was a reasonably even coverage of density observations across the range of variables.

The best-fitting model of large adult Northern Abalone density included only substrate as a significant covariate (Table 7). Large adult Northern Abalone density decreased with increasing rockiness (Substrate; Figure 11). The model explained 85% of the deviance in the data when the year term was included (Table 7) and only 24.5% when the year term was excluded, indicating 71.1% of the variance was explained by the year term. The Tweedie power parameter was 1.08. The model diagnostics indicated that residual patterns were reasonable with small deviations from normality (particularly indicated by the quantile-quantile normal plot, Appendix B, Figure B.23).

When only the 2006-2018 large adult Northern Abalone density was analyzed, the best-fitting model explained 65.6% of the deviance (Table 7). Only tidal currents were significant in the model, with large adult Northern Abalone density decreasing with increasing tidal currents (Figure 11). Model diagnostics were reasonable, and the Tweedie power parameter was estimated at 1.01. When the year term was excluded, the model explained only 65.6% of the deviance, indicating that about 76.9% of the variability in the dataset was explained by the year term. Residual patterns were reasonable with small deviations from normality (particularly indicated by the quantile-quantile normal plot, Appendix B, Figure B.24).

3.3.5 Evaluating the environmental variables in a standardized index of abundance

To estimate a standardized index of abundance for each size category of Northern Abalone in the Southern BC dataset, the best-fitting generalized additive model was used to predict the density of Northern Abalone in each year by holding the other variables in the model at their mean value. The results show that index standardization using GAM predicted different Northern Abalone abundance at index sites than the observed mean density or design-based estimates (Figure 12). In general, the year to year variability was higher for the standardized index and the point estimates were also higher, with the exception of juvenile Northern Abalone. As with the Northern BC dataset, the large effect of the year term (year effect and region effect not accounted for by the environmental variables) in all of the models and the relatively small explanatory power of environmental variables in the absence of year across all datasets translated into only little improvement over the design-based density when Northern Abalone abundance indices were standardized.

3.4 ANALYSIS OF EXISTING NORTHERN ABALONE INDEX SITE SURVEYS DATA AND DESIGN

Looking at the data from individual index sites, the densities of total Northern Abalone ($\geq$ 20 mm shell length) are highly skewed to the right and the standard deviation appears linearly related to the mean (Figure 13). Within sites at the individual quadrat level, there is quite a bit of variation and the coefficients of variation of the site means are typically very large (89% are greater than 1.0). Although it is not shown, this pattern of high variability both within and among sites was not the result of any individual survey region and was consistent across the years.

The coefficient of variation around the observed mean total Northern Abalone ($\geq$ 20 mm shell length) density for each region decreases slowly with increasing numbers of quadrats sampled at each index site (Figure 14). To achieve a coefficient of variation of 1 the sample size would have to be about 75 quadrats per site on average. Similarly, a large number of index sites would have to be added in each region to reduce the coefficient of variation to 0.5 in any year (Figure 15). Taken together, these results indicate that the population variability in total Northern Abalone density (meaning the site-site variability) is large. This would tend to indicate that developing a method for stratification would be useful in increasing the precision of estimates. It would also tend to indicate that there is a lot of variance around the mean (large 95% confidence intervals that might often include zero). The main issue with the existing data is capturing the year over year trends with adequate precision. For instance, the population was most likely declining in the CC and ECHG from 1978-1983, but this wouldn't necessarily have been recognized from the survey data, which likely appeared to be a flat trend. This is similar to the results of the sensitivity test for the continuity of index sites.

The change in detectable difference against sample size (in number of index sites) indicates there are differences among the regions (Figure 16). Point estimates from the survey data (the mean total Northern Abalone ($\geq$ 20 mm shell length) density over the time series and the average number of sites surveyed in the region) indicate that the differences in total Northern Abalone density from year to year must be quite large relative to the observed density to be statistically detectable. For example in ECHG, the mean time series density was ~1.1 abalone/m^2 and the mean sample size was 70 sites. Using those numbers, you could be expected to detect a 0.49 abalone/m^2 difference in total Northern Abalone density in the area (roughly a halving of the density). For the CC, where the mean time series density was approximately 1.5 abalone/m^2 and the effort was about 45 sites. A 35% change in density could be detected with this sample size. In more recent years in these two areas, the increase in total Northern Abalone density (2009-~2016-18) has been large (about a 600% to 800% increase). These are easily detectable using the average time series sample sizes; the same can be said for the WCHG (approximately a 250% increase should be easy to detect with a sample size of around 45).

The two-stage sampling design and resampling of the entire time series of Northern Abalone index sites (across years and regions) is depicted in Figure 17. This simulation was performed to determine the relative gains in precision from adding sites versus adding quadrats, while accounting for both sources of variability. The results show minimal gains by increasing the number of quadrats past approximately eight quadrats. The reduction in variance is influenced more heavily by adding index sites. It would take around 50 sites just to get the 95% confidence intervals to be about half of the mean estimate (indicated by the black line on Figure 17). This is not unexpected, given the results of the preceding analyses.

4 DISCUSSION

This report updates and builds on the analysis of the Northern Abalone Index Site Surveys by Campbell (1996) and Curtis and Zhang (2018), among many others, and attempts to bring together the cumulative 40 plus years of knowledge on how the data for this time series has been collected, extracted, and manipulated (i.e. consolidates current understanding as a reference point for future work). In particular, it provides information on the consistency and availability of survey variables over time, a list of index sites recommended to be excluded from analyses, and sensitivity tests to inform the decision to retain varying numbers of index sites and quadrats in the time series. Changes in the number of quadrats surveyed (i.e. 8 versus 16) and changes in index site continuity had little influence on observed Northern Abalone densities, except for the Southern BC dataset, where the significant difference due to quadrat truncation was likely driven by the small number of survey years included in the analysis. Restricting the number of index sites based on index site continuity was disadvantageous in that it reduced sample size and increased variability, while the overall trends in the annual mean densities stayed fairly similar. For these reasons, index sites were not removed from the time series based on site continuity. This report also represents the first attempt to account for the increase and spread of sea otters and the large decline of sunflower stars in the surveyed index sites, and the corresponding impact on density estimates for the Northern Abalone Index Site Surveys.

The trend in Northern Abalone density over time (decline in early years, low levels in middle years, increase of juveniles in later years) dominates the analyses of index standardization based on environmental variability. Environmental variables explained little of the variance (usually $< 10\%$) in the Northern Abalone density data. There are several potential and interconnected reasons for this. The first is that by design, the index sites did not change locations much from year to year and some index site specific environmental variables are expected to remain fairly constant over time (e.g., Fetch). As the index sites were designed to index the abundance of Northern Abalone, they were expected to stay in the same location from survey to survey. There were some deviations from this pattern, with a median cumulative distance moved for each station of 14.6 m (mean = 206.4 m, s.e. = 48.3 m). Recent research indicates that for repeat visual transects even spatial offsets of 10 m or greater can have a large effect on precision of density estimates, increasing CVs for benthic invertebrates from 0.1 to > 1.0 (Perkins et al. 2018). However, for the Northern Abalone index sites, the largest interannual changes were actually in the addition and subtraction of sites over the time series (see for example Appendix C).

The second reason is that the range of environmental variables included in the analyses may be insufficient to capture the true differences in habitat that occur spatially and temporally. Some of the index sites were specifically chosen because of prior knowledge of their importance to commercial harvest of Northern Abalone (DFO 2016), so for most of these sites the range of environmental variables encountered was likely reduced relative to what may have been available for the entire BC coast. In addition, the environmental variables used in the index standardization were constant over years, including the raster-based and ROMS derived variables. This included variables at each index site that were not expected to change over time, such as site ruggedness or exposure, and those that were expected to change over time and may experience interannual variation, such as salinity, which was highly correlated with temperature. Time-varying environmental characteristics could not be included as there were no ROMS outputs available that extended past 2007. Additionally, many environmental variables collected at the time of the survey could not be included due to the lack of continuity in data collection across the entire time series (1978-2018). Thus, the environmental variables included may not ideally represent the differences among the regions in either the Northern BC or Southern BC datasets, limiting the interpretation of the year effect. Inclusion of time-varying environmental variables should be considered in future analyses as they may improve the index standardization.

A third potential reason that little of the variance in density was explained by environmental variation is that variation among index sites and at each index site over time was very high (see results of power analysis, Section 3.4). In part, this means that for a relatively constant level of an environmental variable at an individual index site, there was a lot of variability in the density estimates. For example, at the site with the highest recorded density the salinity was constant at 32.2 ppt, but the densities over the time series at that site ranged from 0.06 to 16.6 per m^2. This interannual variability at a site was likely driven by external factors, such as fluctuations in harvest (legal and/or illegal) and recruitment or episodic large-scale ocean events. Time-varying mortality, from harvest (e.g., poaching after the closure to all harvesting in 1990, Lessard et al. 2007b; COSEWIC 2009) and changes to predator distribution and densities (e.g., spread of sea otters in BC; Nichol et al. 2015), as well as the highly episodic recruitment that is potentially limited by reduced fertilization success at low spawning densities (Shepherd and Partington 1995; Babcock and Keesing 1999). Since, Northern Abalone are broadcast spawners (Breen and Adkins 1980a), recruitment at an index site may be influenced by connectivity to other Northern Abalone aggregations and broader oceanographic conditions in the region rather than local drivers. Zhang et al. (2007) found weak density dependence in the stock-recruitment relationships for the ECHG and CC regions.

The interannual variability may also represent differences in Northern Abalone density between the regions that were grouped together in the Northern BC and Southern BC datasets. The effect of the region could not be separated from the year effect because often only one region was sampled in each year. However, variability within any given region in Northern BC was generally greater than the difference between regions (in any given set of surveys). Such external factors may have overwhelmed any effect of environmental differences in the Northern BC and Southern BC datasets. Essentially, trying to standardize the index with environmental covariates given these limitations did not realize any appreciable gains in the coefficients of variability.

The ecological setting appeared to be different for Northern Abalone between Northern and Southern BC, supporting the presentation of two separate density estimates in this report. In Northern BC, the dominant environmental variable correlated with Northern Abalone density was salinity. This variable was significant in all eight best-fitting models of Northern Abalone density. Salinity is lower close to the freshwater outputs on the mainland of BC and higher in more western parts of the coast (Thomson 1981). It is important to note that salinity measured from the ROMS model was highly correlated with temperature, so the effect described here could be one of either temperature or salinity. Fetch was another important variable in Northern BC and was significant in five of eight best-fitting models. The tidal currents variable was also significant in five of the eight best-fitting models. This is consistent with past research, which has found fetch or wave exposure, a measure of wave energy, to be important to Northern Abalone density (Tomascik and Holmes 2003; Lessard and Campbell 2007). Results from Northern BC are very much in contrast to the variables found as important in Southern BC. Salinity and Fetch were not significant in any of the best-fitting models for Southern BC and the tidal currents variable was present in only two of the eight models from Southern BC. Current speed and Sea Otter occupancy were significant in the most best-fitting models from Southern BC (four of eight models), whereas these two variables were only significant in Northern BC on a single occasion. This may be because both the WCVI and QCS regions in Southern BC have sea otters present. Sea otters were reintroduced to BC in 1969-1972 (Bigg and MacAskie 1978). A total of 89 animals from Alaska were captured and released into Checleset Bay in the WCVI region. Thus, Checleset Bay had the longest Sea Otter re-occupation in the Southern BC survey regions. Sea otters are at or near equilibrium density with their habitat in the Checleset Bay area and have been since the mid-late 1990s (COSEWIC 2009). The Sea Otter range expanded southward and northward from Checleset Bay over the years, but in QCS region, sea otters have been present since no earlier than 2001 and later than that in some parts of QCS (Nichol et al. 2009). The implication of these results is that there are differences between Northern and Southern BC in how the environment is affecting the density of Northern Abalone. Only the effect of salinity for Northern BC was consistent across all the GAM models. Other effects were not always consistent across the North-South divide or across size categories; for example, higher tidal currents appeared to have a negative effect on juvenile Northern Abalone density, while having a positive effect on large adult Northern Abalone density in Northern BC. The same diverging effects between juveniles and adults were found for Fetch, with higher Fetch having a negative effect on adult, and large adult, Northern Abalone, but a positive effect on juvenile Northern Abalone.

The presence of sea otters at regions in Southern BC had a positive effect on Northern Abalone density. This was a counter-intuitive result, especially given the recent study by Lee et al. (2016) showing a distinct decrease in Northern Abalone density where sea otters occurred in the WCVI and CC regions. The positive effect on density we observed likely reflects a correlation, not causation and may simply reflect the co-occurrence of good Sea Otter habitat and good Northern Abalone habitat. It is unlikely given the predator-prey relationship of these two species (Sloan and Breen 1988; Watson 2000) that sea otters are promoting Northern Abalone population growth. However, the results could be indicative of a trophic cascade, in which sea otters are promoting kelp forest growth by reducing sea urchin abundance, and improving habitat and food availability for Northern Abalone (Lee et al. 2019). Alternatively, a study of Black Abalone (*Haliotis cracherodii*) in California suggests the possibility of a behavioural response to Sea Otter density. Areas of higher Sea Otter density were positively associated with higher Black Abalone density. It was speculated that Sea Otter predation may serve to drive Black Abalone into deep crevice habitat where they were safe from sea otters and poaching in the area (Raimondi et al. 2015). Finally, it is also possible that the effect observed in the data reflects both regional differences in Northern Abalone density and the relatively short time series in Southern BC. Sea otters have occurred at all sites on the WCVI since before the beginning of the Northern Abalone index sites time series in 2003 (Nichol et al. 2015). The WCVI also has the highest densities of Northern Abalone of the regions in Southern BC. The GB region has no recent history of Sea Otter occupation and also has very low Northern Abalone densities. QCS has had higher Northern Abalone densities than GB and a more recent re-occupation of more than half the sites by sea otters. It is very likely that the regional differences in Northern Abalone densities are being captured by the Sea Otter variable, rather than a positive effect of sea otters on Northern Abalone density (due to the grouping of regions together in the Southern BC dataset). A closer look at the data from the CC and QCS regions where the Northern Abalone Index Site Surveys were initiated prior to the re-occupation by sea otters might help resolve the Sea Otter-Northern

Abalone interaction (e.g., Lee et al. 2019).

4.1 FUTURE DIRECTIONS

In our analyses, we retained all the data except for index sites that were surveyed only once as part of exploratory surveys or for non-index purposes (e.g., environmental impact assessments), and index sites where no size-frequency data or quadrat-level data were available. Sites surveyed between 2000-2016 that were previously excluded in Curtis and Zhang (2018) due to habitat characteristics were included because their removal had no discernable effect on overall trends. We recommend that a consistent method to remove index sites be developed for the longer time series (i.e. 1978 to present), particularly for index sites where habitat may have changed over time. For example, a consistent method of removing index sites where habitat is unsuitable for Northern Abalone or where poor dive conditions affected observations, or did not allow all 16 quadrats to be surveyed, needs to be developed. Currently, the dataset includes index sites where less than eight quadrats were sampled, as in previous analyses of the time series. Additionally, further consideration of index site continuity over time is warranted given the significant effect that changes in the number of index sites surveyed had on total Northern Abalone density, in terms of trend detection and variance.

This report also attempts to capture the impact of changing predator abundance on the time series of Northern Abalone density. However, sunflower stars are a mobile predator (Montgomery 2014) and the observations of Sunflower Star abundance in the surveyed quadrats may not capture abundance at an index site throughout the year. Large declines in Sunflower Star abundance since 2013, due to sea star wasting disease (Schultz et al. 2016; Harvell et al. 2019), were expected to have a positive effect on Northern Abalone density in BC. However, this could not be statistically detected with the discrete quadrat-level data that were available. Additionally, the Sea Otter occupation time based on presence/absence of at least three sea otters during summer, may not be a good measure of Sea Otter predation effects on Northern Abalone. It cannot account for the difference between a large raft of sea otters foraging in an area versus a small raft, or for different amounts of time spent foraging at the index site, which may all have a different effect on Northern Abalone density. The present analyses also do not include the abundance of other Sea Otter prey at the index sites, such as sea urchins, which may contribute to variation in predation pressure on Northern Abalone between the index sites. Future exploration of ways to incorporate Sunflower Star and Sea Otter predation could further help to standardize the Northern Abalone Index Site Surveys time series and help clarify their contribution to the abundance estimates and trends.

Northern Abalone density is highly variable in the time series (density CV $>$ 1.0 for 58$\%$ of the year-region combinations), reducing the power of the survey to detect changes over time. More index sites (100-150) in each region would reduce the variability for most year-region combinations to a CV $<$ 1.0 and would have a greater impact on power than increasing the number of quadrats at each site. Future research could focus on changes to the survey design that would increase sampling effort (i.e. more sites) while conserving the 40 plus year history. This may require a calibration in the field to develop a correction factor between different survey designs (e.g., Campbell 1996; Sloan and Breen 1988; Cripps and Campbell 1998).

Finally, as Northern Abalone is an endangered species with low densities, particularly in

Southern BC, reducing variability is important in detecting changes in abundance, setting objectives and measuring recovery or further loss. Therefore, standardization based on environmental variables should be considered in future analyses, despite explaining relatively little of the variation in Northern Abalone density herein. The significant environmental variables from the GAM models (1978-2018) for each Northern Abalone size category in the Northern BC and Southern BC datasets were the best variables identified for inclusion in future standardization of the time series. These covariates could be used together with the Bayesian hurdle model developed by Curtis and Zhang (2018) for the Northern Abalone Index Site Surveys. Additionally, as salinity was highly correlated with temperature, the salinity effect that was detected may actually be a temperature effect. Future analyses should consider the importance of time-varying temperature as a covariate. Despite the lack of appreciable gains in the coefficient of variation when standardizing with environmental covariates, the overall trends in the densities for Northern BC were robust. If considering combining regions in Northern BC or Southern BC, it is important to bear in mind the confounding effects of region and year on mean densities in these time series. In the Southern BC dataset in particular, environmental covariates likely represent regional differences in the estimated density. This report is a first step towards standardization of the Northern Abalone Index Sites Survey time series based on methodology changes and environmental variability. A next step would be to explore standardization with environmental covariates for each region separately. Furthermore, a pilot project to measure local environmental conditions (e.g., temperature and salinity) over a range of index sites could help to identify important variables to continue measuring and could provide data on a finer spatial and temporal scale, which may improve standardization efforts.

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6 REFERENCES

Adkins, B.E. 1996. Abalone surveys in south coast areas during 1982, 1985 and 1986. *In* Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1993 and 1994. *Edited by* C.M Hand and B. Waddell. Can. MS Rep. Fish. Aquat. Sci. 2089: 72–96.

Adkins, B.E., and Stefanson, A.P. 1979. North coast abalone survey in harvested areas, November 1978. Fish. Mar. Serv. MS Rep. 1500: 15 p.

Anderson, S.C., Grandin, C., Grinnell, M.H., Ricard, D., Ismay, C., Solomon, N., and Marwick, B. 2019. CSASdown: An R Markdown template for creating CSAS research documents. R package version 0.0.7.

Anderson, S.C., Keppel, E.A., and Edwards, A.M. (In press). A reproducible data synopsis for over 100 species of British Columbia groundfish. Can. Sci. Advis. Sec. Res. Doc.

Atkins, M., and Lessard, J. 2004. Survey of Northern Abalone, *Haliotis kamtschatkana*, populations along northwest Vancouver Island, British Columbia, May 2003. Can. MS Rep. Fish. Aquat. Sci. 2690: 12 p.

Atkins, M., Lessard, J., and Campbell, A. 2004. Resurvey of Northern Abalone, *Haliotis kamtschatkana*, populations in southeast Queen Charlotte Islands, British Columbia, April 2002. Can. MS Rep. Fish. Aquat. Sci. 2704: 37 p.

Babcock, R., and Keesing, J. 1999. Fertilization biology of the abalone *Haliotis laevigata*: Laboratory and field studies. Can. J. Fish. Aquat. Sci. 56: 1668–1678.

Bigg, M.A., and MacAskie, I.B. 1978. Sea otters re-established in British Columbia. J. Mammal. 59(4): 874–876.

Boutillier, J., Carolsfeld, W., Breen, P.A., and Bates, K. 1984. Abalone survey in the Estevan Group and Aristazabal Island May, 1983. Can. MS Rep. Fish. Aquat. Sci. 1747: iv + 60 p.

Boutillier, J., Carolsfeld, W., Breen, P.A., Farlinger, S., and Bates, K. 1985. Abalone resurvey in the southeast Queen Charlotte Islands, July 1984. Can. MS Rep. Fish. Aquat. Sci. 1818: 87 p.

Breen, P.A. 1979. Observations of the commercial abalone fishery made from the patrol vessel "Cutter Rock", April 13-21, 1979. Confidential Report Series, Canada Fisheries and Marine Service 43: iii + 43 p.

Breen, P.A. 1986. Management of the British Columbia fishery for Northern Abalone (*Haliotis kamtschatkana*). *In* North Pacific workshop on stock assessment and management of invertebrates. *Edited by* G.S Jamieson and N. Bourne. Can. Spec. Publ. Fish. Aquat. Sci. 92: 300–312.

Breen, P.A., and Adkins, B.E. 1979. A survey of abalone populations on the east coast of the Queen Charlotte Islands, August 1978. Can. MS Rep. Fish. Aquat. Sci. 1490: 125 p.

Breen, P.A., and Adkins, B.E. 1980a. Spawning in a British Columbia population of Northern Abalone, *Haliotis kamtschatkana.* The Veliger 23(2): 177–179.

Breen, P.A., and Adkins, B.E. 1980b. Observations of abalone populations in Emily Carr Inlet and Lotbiniere Bay, April 1980. Can. MS Rep. Fish. Aquat. Sci. 1576: 17 p.

Breen, P.A., and Adkins, B.E. 1981. Abalone surveys and tagging conducted during 1979. Can. MS Rep. Fish. Aquat. Sci. 1623: iii + 88 p.

Breen, P.A., Adkins, B.E., and Sprout, P.E. 1982. Abalone populations on the west coast of Banks Island, June 1980. Can. MS Rep. Fish. Aquat. Sci. 1640: iii + 42 p.

Burt, J.M., Tinker, M.T., Okamoto, D.K., Demes, K.W., Holmes, K., and Salomon, A.K. 2018. Sudden collapse of a mesopredator reveals its complementary role in mediating rocky reef regime shifts. Proc. R. Soc. 285(1883): 9 p.

Campbell, A. 1996. An evaluation of abalone surveys off the southeast Queen Charlotte Islands. *In* Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1993 and 1994. *Edited by* C.M Hand and B. Waddell. Can. MS Rep. Fish. Aquat. Sci. 2089: 111–131.

Campbell, A. 2000. Review of Northern Abalone, *Haliotis kamtschatkana*, stock status in British Columbia. *In* Workshop on rebuilding abalone stocks in British Columbia. *Edited by* A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 130: 41–50.

Campbell, A., Brouwer, D., Rogers, J., and Miller, D.C. 2000. Abalone resurvey in southeast Queen Charlotte Islands, 1998. Can. MS Rep. Fish. Aquat. Sci. 2528: 30 p.

Campbell, A., and Cripps, K. 1998. Survey of abalone populations at Stryker Island, Tribal Group and Simonds Group, Central Coast of British Columbia, May, 1997. Can. MS Rep. Fish. Aquat. Sci. 2451: 21 p.

Campbell, A., Lessard, J., and Jamieson, G.S. 2003. Fecundity and seasonal reproduction of Northern Abalone, *Haliotis kamtschatkana*, in Barkley Sound, Canada. Journal of Shellfish Research 22(3): 811–818.

Campbell, A., Manley, I., and Carolsfeld, W. 1992. Size at maturity and fecundity of the abalone, *Haliotis kamtschatkana*, in northern British Columbia. Can. MS. Rep. Fish. Aquat. Sci. 2169: 47–65.

Campbell, A., Winther, I., Adkins, B.E., Brouwer, D., and Miller, D.C. 1998. Survey of the Northern Abalone (*Haliotis kamtschatkana*) in the Central Coast of British Columbia, May 1997. Can. Sci. Advis. Sec. Res. Doc. 88/89: 28 p.

Carolsfeld, W., Farlinger, S., Kingzett, B.C., Sloan, N.A., and Thomas, G. 1988. Abalone resurvey in the southeast Queen Charlotte Islands, June 1987. Can. MS Rep. Fish. Aquat. Sci. 1966: 90 p.

Champley, S. 2018. Pwr: Basic functions for power analysis. R package version 1.2-2.

Cohen, J. 1988. Statistical power analysis for the behavioral sciences. *In* 2nd Edition. Lawrence Erlbaum Associates, New York.

COSEWIC. 2009. COSEWIC assessment and update status report on the Northern Abalone, *Haliotis kamtschatkana* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa.

Cripps, K., and Campbell, A. 1998. Survey of abalone populations at Dallain Point and Higgins Pass, central coast of British Columbia, 1995-96. Can. MS Rep. Fish. Aquat. Sci. 2445: 31 p.

Curtis, D.L., and Zhang, Z. 2018. Northern Abalone, *Haliotis kamtschatkana*, stock status and re-analysis of index site surveys in British Columbia 2000-2016. Can. MS Rep. Fish. Aquat. Sci. 3162: vi + 161 p.

Davies, K., Atkins, M., and Lessard, J. 2006. Survey of Northern Abalone, *Haliotis kamtschatkana*, populations in Queen Charlotte and Johnstone Straits, British Columbia, May 2004. Can. MS Rep. Fish. Aquat. Sci. 2743: iii + 17 p.

Davies, S.C., Gregr, E.J., Lessard, J., Bartier, P., and Wils, P. (In press). Development of bathymetric elevation models for ecological analyses in Pacific Canadian coastal waters. Can. Tech. Rep. Fish. Aquat. Sci.

DFO. 2012. Action plan for the Northern Abalone (*Haliotis kamtschatkana*) in Canada. Species At Risk Act Action Plan Series. DFO: vii + 65 p.

DFO. 2016. Review of dive survey methods for Northern Abalone in British Columbia. DFO Can. Sci. Advis. Sec. Sci. Resp. 2016/044.

Efron, R., and Tibshirani, R. 1993. An introduction to the bootstrap. Chapman and Hall, London.

Egli, T.P., and Lessard, J. 2011. Survey of Northern Abalone, *Haliotis kamtschatkana*, population in the Strait of Georgia, British Columbia, October 2009. Can. MS Rep. Fish. Aquat. Sci. 2955: iii + 12 p.

Farlinger, S. 1990. Review of the biological basis for management of the British Columbia abalone fishery. *In* Shellfish stock assessments for the west coast of Canada in 1990 as reviewed by the Pacific Stock Assessment Review Committee (PSARC). *Edited by* G.A. Thomas. Can. MS Rep. Fish. Aquat. Sci. 2099: 41–65.

Farlinger, S., and Bates, K. 1986. Abalone survey in the Estevan Group and Aristazabal Island, June 1985. Can. MS Rep. Fish. Aquat. Sci. 1896: 45 p.

Farlinger, S., and Campbell, A. 1992. Fisheries management and biology of Northern Abalone, *Haliotis kamtschatkana* in the northeast Pacific. *In* Abalone of the world - Biology, fisheries and culture. *Edited by* S.A. Shepherd, M.J. Tegner, S.A. Guzmán del Próo. Fishing News Books, Oxford. pp. 395–406.

Farlinger, S., Thomas, G.A., Winther, I., and Carolsfeld, W. 1991. Abalone resurvey in the Estevan Group and Aristazabal Island, June 1989. Can. MS Rep. Fish. Aquat. Sci. 2104: 39 p.

Garshelis, D.L., and Garshelis, J.A. 1984. Movements and management of sea otters in Alaska. Wildl. Manag. 48: 665–677.

Geiger, D.L. 2000. Distribution and biogeography of Haliotidae (Gastropoda: Vetigastropoda) world-wide. Bolleffino Malacologico 35: 57–120.

Gregr, E.J., and Haggarty, D. 2016. Background substrate and the integration of nearshore and deep water classifications (draft). SciTech Environmental Consulting, Vancouver, B.C.

Griffiths, A.M., and Gosselin, L.A. 2008. Ontogenetic shift in susceptibility to predators in juvenile

Northern Abalone, *Haliotis kamtschatkana.* Journal of Experimental Marine Biology and Ecology 360(2): 85–93.

Gunderson, D.R. 1993. Surveys of fisheries resources. John Wiley & Sons, New York, NY.

Hankewich, S., and Lessard, J. 2008. Resurvey of Northern Abalone, *Haliotis kamtschatkana*, populations along the Central Coast of British Columbia, May 2006. Can. MS Rep. Fish. Aquat. Sci. 2838: vi + 41 p.

Hankewich, S., Lessard, J., and Grebeldinger, E. 2008. Resurvey of Northern Abalone, *Haliotis kamtschatkana*, populations in southeast Queen Charlotte Islands, British Columbia, May 2007. Can. MS Rep. Fish. Aquat. Sci. 2839: vii + 39 p.

Harbo, R. 1997. Abalone dive fishery (closed). *In* Pacific commercial fishery updates for invertebrate resources (1994). *Edited by* R. Harbo and K. Hobbs. Can. MS Rep. Fish. Aquat. Sci. 2369: 86–92.

Harvell, C.D., Montecino-Latorre, D., Caldwell, J.M., Burt, J.M., Bosley, K., Keller, A., Heron, S.F., Salomon, A.K., Lee, L., Pontier, O., Pattengill-Semmens, C., and Gaydos, J.K. 2019. Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia Helianthoides*). Science Advances 5(1): 9 p.

Hijmans, R.J. 2019. Raster: Geographic data analysis and modeling. R package version 2.9-23. cran.r-project.org/package=raster.

Jameson, R.J. 1989. Movements, home ranges, and territories of male sea otters off central California. Mar. Mamm. Sci. 5: 159–172.

Jamieson, G. 2001. Review of status of Northern Abalone. Canadian Field Naturalist 115(4): 555–563.

Lee, L.C., Thorley, J., Watson, J., Reid, M., and Salomon, A.K. 2019. Diverse knowledge systems reveal social-ecological dynamics that inform species conservation status. Conservation Letters 12(2): 11 p.

Lee, L.C., Watson, J.C., Trebilco, R., and Salomon, A.K. 2016. Indirect effects and prey behavior mediate interactions between an endangered prey and recovering predator. Ecosphere 7(12): 26 p.

Lessard, J., Atkins, M., and Campbell, A. 2007a. Resurvey of Northern Abalone, *Haliotis kamtschatkana*, populations along the central coast of British Columbia, April 2001. Can. MS Rep. Fish. Aquat. Sci. 2791: vi +35 p.

Lessard, J., and Campbell, A. 2007. Describing Northern Abalone, *Haliotis kamtschatkana*, habitat: Focusing rebuilding efforts in British Columbia, Canada. Journal of Shellfish Research 26(3): 677–686.

Lessard, J., Campbell, A., Zhang, Z., MacDougall, L., and Hankewich, S. 2007b. Recovery potential assessment for the Northern Abalone (*Haliotis kamtschatkana*) in Canada. Can. Sci. Advis. Sec. Res. Doc. 061: 107 p.

Lessard, J., and Egli, T.P. 2011. Survey of Northern Abalone, *Haliotis kamtschatkana*, population in Queen Charlotte Strait, British Columbia, May 2009. Can. MS Rep. Fish. Aquat. Sci. 2959:

iv + 17 p.

Marchand, P., and Gill, D. 2018. Waver: Calculate fetch and wave energy. R package version 0.2.1.

Masson, D., and Fine, I. 2012. Modeling seasonal to interannual ocean variability of coastal British Columbia. Journal of Geophysical Research: Oceans 117: C10019, doi:10.1029/2012JC008151.

Maunder, M.N., and Punt, A.E. 2004. Standardizing catch and effort data: A review of recent approaches. Fisheries Research 70(2-3): 141–159.

Montgomery, E.M. 2014. Predicting crawling speed relative to mass in sea stars. Journal of Experimental Marine Biology and Ecology 458: 27–33.

Moss, G.A., and Tong, L. 1992. Effect of stage of larval development on the settlement of the abalone *Haliotis Iris*. New Zealand Journal of Marine and Freshwater Research 1992(26): 69–73.

Nephin, J., Gregr, E.J., St. Germain, C., Fields, C., and Finney, J.L. (In press). Development and application of a habitat suitability modelling framework to a collection of species on Canada's Pacific coast. Can. Sci. Advis. Sec. Res. Doc. in press.

Neuman, M.J., Wang, S., Busch, S., Friedman, C., Gruenthal, K., Gustafson, R., Kushner, D., Stierhoff, K., Vanblaricom, G., and Wright, S. 2018. A status review of Pinto Abalone (*Haliotis kamtschatkana*) along the west coast of North America: Interpreting trends, addressing uncertainty, and assessing risk for a wide-ranging marine invertebrate. J. Shell. Res. 37(4): 869–910.

Nichol, L.M., Boogaards, M.D., and Abernathy, R. 2009. Recent trends in the abundance and distribution of sea otters (*Enhydra lutris*) in British Columbia. Can. Sci. Advis. Sec. Res. Doc. 016: iv + 16p.

Nichol, L.M., Watson, J.C., Abernethy, R., Rechsteiner, E., and Towers, J. 2015. Trends in the abundance and distribution of sea otters (*Enhydra lutris*) in British Columbia updated with 2013 survey results. Can. Sci. Advis. Sec. Res. Doc. 039: vii + 31 p.

Perkins, N.R., Hosack, G.R., Foster, S.D., Hill, N.A., and Barrett, N.S. 2018. Spatial properties of sessile benthic organisms and the design of repeat visual survey transects. Aqua. Cons.: Mar. Freshw. Ecosyst. 29(1): 59–71.

Quayle, D.B. 1971. Growth, morphometry and breeding in the British Columbia abalone. Fish. Res. Board Can. Tech. Rep. 279: 84 p.

Raimondi, P., Jurgens, L.J., and Tinker, M.T. 2015. Evaluating potential conservation conflicts between two listed species: Sea Otters and Black Abalone. Ecology 96(11): 3102–3108.

R Core Development Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.

Ripley, B., and Lapsley, M. 2017. RODBC: ODBC database access. R package version 1.3-15.

Roberts, R. 2003. A perspective from New Zealand on abalone stock enhancement, with emphasis on early life history. Can. Tech. Rep. Fish. Aquat. Sci. 2482: 77–96.

Rogers-Bennett, L., Allen, B.L., and Rothaus, D.P. 2011. Status and habitat associations of the threatened Northern Abalone: Importance of kelp and coralline algae. Aquatic Conservation: Marine and Freshwater Ecosystems 21(6): 573–581.

Sappington, J.M. 2007. Quantifying landscape ruggedness for animal habitat analysis: A case study using bighorn sheep in the Mojave Desert. Journal of Wildlife Management 71(5): 1419–1426.

Schultz, J.A., Cloutier, R.N., and Côté, I.M. 2016. Evidence for a trophic cascade on rocky reefs following sea star mass mortality in British Columbia. PeerJ 4: 26 p.

Shepherd, S., and Partington, D. 1995. Studies on Southern Abalone (Genus Haliotis). XVI. Recruitment, habitat and stock relations. Mar. Freshwater Res 46: 669–680.

Sloan, N.A., and Breen, P.A. 1988. Northern Abalone, *Haliotis kamtschatkana*, in British Columbia: Fisheries and synopsis of life history information. Can. Spec. Publ. Fish. Aquat. Sci. 103: 46 p.

Szarzi, N.J., Quinn, T.J., and McBride, D.N. 1995. Assessment of shallow-water clam resources: Case study of razor clams, eastern Cook Inlet, Alaska. ICES mar. Sci. Symp. 199: 274–286.

Thomas, G., and Campbell, A. 1996. Abalone resurvey in Aristazabal Island, the Estevan Group and Banks Island, June 1993. *In* Invertebrate working papers reviewed by the Pacific Stock Assessment Review Committee (PSARC) in 1993 and 1994. *Edited by:* C.M Hand and B. Waddell. Can. Tech. Rep. Fish. Aquat. Sci. 2089: 97–109.

Thomas, G., Farlinger, S., Carolsfeld, W., and Rupert, P. 1992. Abalone resurvey in the southeast Queen Charlotte Islands in 1990. Can. MS Rep. Fish. Aquat. Sci. 2166: v + 93 p.

Thompson, S.K. 1992. Sampling. John Wiley & Sons, New York, NY.

Thomson, R.E. 1981. Oceanography of the British Columbia coast. Min. of Supply and Services Canada, Ottawa.

Tomascik, T., and Holmes, H. 2003. Distribution and abundance of *Haliotis kamtschatkana* in relation to habitat, competitors and predators in the Broken Group Islands, Pacific Rim National Park Reserve of Canada. J. Shell. Res. 22(3): 831–838.

Tweedie, M.C.K. 1984. An index which distinguishes between some important exponential families. *Edited by* J. K. Ghosh and J. Roy. *In Statistics: Applications and New Directions.* Calcutta: Indian Statistical Institute. pp. 579–604.

Watson, J.C. 2000. The effects of sea otters (*Enhydra lutris*) on abalone (*Haliotis* spp.) populations. *In*Workshop on rebuilding abalone stocks in British Columbia. *Edited by* A. Campbell. Can. Spec. Publ. Fish. Aquat. Sci. 130: 123–132.

Weinberg, K.L., and Kotwicki, S. 2008. Factors influencing net spreadand sea floor contact of a survey bottom trawl. Fish. Res. 93: 265–279.

Winther, I., Campbell, A., Thomas, G.A., Adkins, B.E., and Clapp', B.G. 1995. Abalone resurvey in the southeast Queen Charlotte Islands in 1994. Can. MS Rep. Fish. Aquat. Sci. 2273: 46 p.

Withler, R., Campbell, A., Li, S., Brouwer, D., Supernault, J., and Miller, K. 2003. Implications of high levels of genetic diversity and weak population structure for the rebuilding of Northern Abalone in British Columbia, Canada. J. Shell. Res. 22: 839–847.

Wood, S.N. 2006. Generalized additive models: An introduction with R, second edition. CRC Press: 496 p.

Wood, S.N., and Augustin, N.H. 2002. GAMs with integrated model selection using penalized regression splines and applications to environmental modelling. Ecol. Model. 157(2): 157–177.

Zhang, Z., Campbell, A., and Lessard, J. 2007. Modeling Northern Abalone, *Haliotis kamtschatkana*, population stock and recruitment in British Columbia. J. Shell. Res. 26(4): 1099–1107.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., and Smith, G.M. 2009. Mixed effects models and extensions in ecology with R. Springer-Verlag, New York.

7 TABLES

Table 1. Northern Abalone Index Site Surveys conducted in different regions in BC over time. Values indicate the number of sites surveyed within a given region. NS indicates that no survey was conducted in any of the six regions in a given year. Numbers in brackets represent the number of sites after site exclusion for data analysis (see Table 4). Surveys using the Breen Survey Method were also conducted in JS in 1986 (2 sites, Davies et al. 2006) and 2004 (36 sites, Adkins 1996), but are not included here.

		Region						
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**	**References**
1978		108(51)	12					Adkins and Stefanson (1979), Breen and Adkins (1979)
1979		10(9)	14					Breen and Adkins (1981)
1980			19					Breen and Adkins (1980b), Breen et al. (1982)
1981	NS							
1982					3(2)			Adkins (1996)
1983			42					Boutillier et al. (1984)
1984		70						Boutillier et al. (1985)
1985			28		12			Farlinger and Bates (1986), Adkins (1996)
1986	NS							
1987		70(69)						Carolsfeld et al. (1988)
1988	NS							
1989			26					Farlinger et al. (1991)
1990		69						Thomas et al. (1992)
1991	NS							
1992	NS							
1993			33(32)					Thomas and Campbell (1996)
1994		70(69)						Winther et al. (1995)
1995	NS							
1996	NS							
1997			135(46)					Campbell et al. (1998)
1998		115						Campbell et al. (2000)
1999	NS							
2000	NS							
2001			55					Lessard et al. (2007a), Curtis and Zhang (2018)
2002		68						Atkins et al. (2004), Curtis and Zhang (2018)
2003						32(18)		Atkins and Lessard (2004), Curtis and Zhang (2018)
2004				26(19)				Davies et al. (2006) , Curtis and Zhang (2018)
2005					19			Lessard et al. (2007b)
2006			68					Hankewich and Lessard (2008), Curtis and Zhang (2018)
2007		82						Hankewich et al. (2008), Curtis and Zhang (2018)
2008						23	40(39)	Curtis and Zhang (2018)
2009				34	30			Egli and Lessard (2011), Lessard and Egli (2011), Curtis and Zhang (2018)
2010	NS							
2011			76					Curtis and Zhang (2018)

Year	Survey	ECHG	CC	QCS	GB	WCVI	WCHG	References
2012		84						Curtis and Zhang (2018)
2013						62	48	Curtis and Zhang (2018)
2014				34				Curtis and Zhang (2018)
2015	NS							
2016			78					Curtis and Zhang (2018)
2017		84						Unpublished (except in this document)
2018						59	50	Unpublished (except in this document)
2019				34	47			Unpublished

Table 2. Summary of methodological changes in the number of quadrats surveyed. NS indicates that no survey was conducted in any of the six regions in a given year. Zeros identify the number of surveys in which no Northern Abalone were encountered in the first eight quadrats. Numbers listed under each region indicate the targeted total number of quadrats to be surveyed when no Northern Abalone were encountered in the first eight quadrats (according to the survey plan).

			Region					
Year	**Survey**	**Zeros**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		4	8	8				
1979		0	8	8				
1980		1	8	8[a]				
1981	NS							
1982		0			8			
1983		2		8				
1984		11	8[a]					
1985		0		8		8		
1986		0			8			
1987		3	8					
1988	NS							
1989		2		8				
1990		7	8[a]					
1991	NS							
1992	NS							
1993		4		8[b]				
1994		28	16[c]					
1995	NS							
1996	NS							
1997		11		8 + 16[d]				
1998		16	16					
1999	NS							
2000	NS							
2001		20		8[a]				
2002		24	8[a]					
2003		24					8	
2004		39			8[a]			
2005		17				8		
2006		24		16				
2007		28	16					
2008		22					8	8[a]
2009		49			8[a]	8[a]		
2010	NS							
2011		9		16[e]				
2012		13	16					
2013		32			16		8 + 16[f]	8 + 16[f]
2014		25			16[e]			
2015	NS							
2016		4		16				
2017		9	16					
2018		20					16	16

[a] 16 quadrats also identified in the data
[b] 24 quadrats also identified in the data
[c] Quadrat counts in the data were all ≥ 32
[d] 32 quadrats also identified in the data
[e] 8 quadrats also identified in the data
[f] Survey plan consisted of priority levels assigned to sites (if no Northern Abalone were found in the first 8 quadrats, surveying was stopped in low priority sites but continued in high priority sites)

Table 3. Summary of methodological changes in the recording of cryptic Northern Abalone observations, where Y indicates observations recorded through one of seven methods, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	Survey	ECHG	CC	QCS	GB	WCVI	WCHG
1978		Y[a]	N				
1979		Y[a]	Y[b]				
1980			Y[c]				
1981	NS						
1982					N		
1983			Y[c]				
1984		Y[d]					
1985			Y[c]		N		
1986					N		
1987		Y[d]					
1988	NS						
1989			Y[d]				
1990		Y[d]					
1991	NS						
1992	NS						
1993			Y[d]				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						N	
2004				N			
2005					N		
2006			Y[e]				
2007		Y[e]					
2008						Y[f]	Y[e]
2009				N	N		
2010	NS						
2011			N				
2012		N					
2013						Y[f]	N
2014				Y[f]			

Year	Survey	ECHG	CC	QCS	GB	WCVI	WCHG
2015	NS						
2016			Y[g]				
2017		Y[g]					
2018						Y[g]	Y[g]

[a] All quadrats at limited sites searched for cryptic Northern Abalone; cryptic counts not recorded separately from emergent counts (QCryptic flag in Database is TRUE for all quadrats searched)

[b] All quadrats at limited sites searched for cryptic Northern Abalone; cryptic counts not recorded separately from emergent counts (QCryptic flag in Database is FALSE for all quadrats searched)

[c] All quadrats at all sites searched for cryptic Northern Abalone; cryptic counts not recorded separately from emergent counts (QCryptic flag in Database is TRUE for all quadrats)

[d] All quadrats at all sites searched for cryptic Northern Abalone; cryptic counts recorded separately from emergent counts (Qcryptic flag in Database is TRUE for all quadrats)

[e] Limited quadrats searched for cryptic Northern Abalone (contrary to survey protocol); cryptic counts recorded separately from emergent counts (QCryptic flag in Database is TRUE for only those quadrats with cryptic Northern Abalone)

[f] Quadrats 2, 4, 6, 8, at all sites searched for cryptic Northern Abalone, regardless of substrate; cryptic counts recorded separately from emergent counts (QCryptic flag in Database is TRUE for quadrats 2, 4, 6, 8 only)

[g] Quadrats 2, 4, 6, 8, at all sites searched for cryptic Northern Abalone only when substrate allowed for turning of rocks; cryptic counts recorded separately from emergent counts (QCryptic flag in Database is TRUE for quadrats searched)

Table 4. Index site records excluded from analyses due to: (A) No size-frequency data; (B) One-off survey; (C) Fish farm survey; and (D) No quadrat-level data.

Region	Year	Site	Reason	Region	Year	Site	Reason	Region	Year	Site	Reason
ECHG	1978	12	A	ECHG	1987	52	A	CC	1997	SP10	B
ECHG	1978	14	A	ECHG	1994	76	A	CC	1997	SP11	B
ECHG	1978	17	A	CC	1993	44	A	CC	1997	SP12	B
ECHG	1978	19	A	WCHG	2008	G15	A	CC	1997	SP13	B
ECHG	1978	21	A	CC	1997	AR10	B	CC	1997	SP15	B
ECHG	1978	22	A	CC	1997	AR106	B	CC	1997	SP16	B
ECHG	1978	23	A	CC	1997	AR15	B	CC	1997	SP18	B
ECHG	1978	25	A	CC	1997	AR02	B	CC	1997	SP19	B
ECHG	1978	29	A	CC	1997	AR20	B	CC	1997	SP02	B
ECHG	1978	30	A	CC	1997	AR91	B	CC	1997	SP20	B
ECHG	1978	31	A	CC	1997	CB01	B	CC	1997	SP24	B
ECHG	1978	35	A	CC	1997	CB11	B	CC	1997	SP27	B
ECHG	1978	37	A	CC	1997	CB02	B	CC	1997	SP28	B
ECHG	1978	38	A	CC	1997	R10	B	CC	1997	SP04	B
ECHG	1978	40	A	CC	1997	R159	B	CC	1997	SP06	B
ECHG	1978	41	A	CC	1997	R172	B	CC	1997	SP07	B
ECHG	1978	43	A	CC	1997	R223	B	CC	1997	SP09	B
ECHG	1978	49	A	CC	1997	R27	B	CC	1997	ST129	B
ECHG	1978	50	A	CC	1997	R295	B	CC	1997	ST133	B
ECHG	1978	51	A	CC	1997	R39	B	CC	1997	ST150	B
ECHG	1978	53	A	CC	1997	R45	B	CC	1997	ST214	B
ECHG	1978	55	A	CC	1997	R46	B	CC	1997	ST228	B
ECHG	1978	56	A	CC	1997	R47	B	CC	1997	ST238	B
ECHG	1978	57	A	CC	1997	R77	B	CC	1997	ST263	B
ECHG	1978	59	A	CC	1997	R770	B	CC	1997	ST284	B
ECHG	1978	65	A	CC	1997	WR178	B	CC	1997	ST298	B
ECHG	1978	66	A	CC	1997	WR97	B	CC	1997	ST316	B
ECHG	1978	67	A	CC	1997	EH00	B	CC	1997	ST345	B
ECHG	1978	69	A	CC	1997	EH16	B	CC	1997	ST4113	B
ECHG	1978	70	A	CC	1997	EH17	B	CC	1997	ST4142	B
ECHG	1978	78-01	A	CC	1997	EH22	B	CC	1997	ST518	B
ECHG	1978	78-02	A	CC	1997	EH24	B	CC	1997	ST531	B
ECHG	1978	78-04	A	CC	1997	EH25	B	CC	1997	ST552	B
ECHG	1978	78-101	A	CC	1997	EH29	B	CC	1997	ST556	B
ECHG	1978	78-11	A	CC	1997	EH32	B	CC	1997	ST560	B
ECHG	1978	78-110	A	CC	1997	EH33	B	WCVI	2003	2	B
ECHG	1978	78-116	A	CC	1997	EH35	B	WCVI	2003	6	B
ECHG	1978	78-117	A	CC	1997	EH36	B	WCVI	2003	7	B
ECHG	1978	78-20	A	CC	1997	EH37	B	WCVI	2003	8	B
ECHG	1978	78-22	A	CC	1997	EH40	B	WCVI	2003	14	B
ECHG	1978	78-23	A	CC	1997	EH45	B	WCVI	2003	17	B
ECHG	1978	78-26	A	CC	1997	EH49	B	WCVI	2003	28	B
ECHG	1978	78-27	A	CC	1997	EH51	B	WCVI	2003	31	B
ECHG	1978	78-35	A	CC	1997	EH54	B	WCVI	2003	33	B
ECHG	1978	78-39	A	CC	1997	EH57	B	WCVI	2003	36	B
ECHG	1978	78-43	A	CC	1997	EH61	B	WCVI	2003	38	B
ECHG	1978	78-44	A	CC	1997	EH63	B	WCVI	2003	43	B
ECHG	1978	78-45	A	CC	1997	EH68	B	WCVI	2003	45	B
ECHG	1978	78-46	A	CC	1997	EH09	B	WCVI	2003	48	B
ECHG	1978	78-47	A	CC	1997	EP22	B	QCS	2004	F01	C
ECHG	1978	78-48	A	CC	1997	EP266	B	QCS	2004	F02	C
ECHG	1978	78-49	A	CC	1997	EP76	B	QCS	2004	F03	C
ECHG	1978	78-54	A	CC	1997	SI02	B	QCS	2004	F05	C
ECHG	1978	78-60	A	CC	1997	SI03	B	QCS	2004	F06	C
ECHG	1978	78-86	A	CC	1997	SI12	B	QCS	2004	F07	C
ECHG	1978	78-90	A	CC	1997	SI23	B	QCS	2004	F08	C
ECHG	1978	78-93	A	CC	1997	SI25	B	GB	1982	10	D
ECHG	1979	79-60	A	CC	1997	SP01	B				

Table 5. Potential explanatory environmental variables for standardizing indices of Northern Abalone density.

Variable	Unit	Definition	Original Scale	Source
Salinity	ppt	Mean summer bottom salinity (1998-2007)	3 km grid	Regional Ocean Model System (ROMS); Masson and Fine (2012)
Temperature	°C	Mean summer bottom temperature (1998-2007)	3 km grid	Regional Ocean Model System (ROMS); Masson and Fine (2012)
Tidal current speed (Tides)	$m \cdot sec^{-1}$	Mean summer tidal current speed (1998-2007)	3 km grid	Regional Ocean Model System (ROMS); Masson and Fine (2012)
Mean current speed (Currents)	$m \cdot sec^{-1}$	Mean non-tidal summer current speed (1998-2007)	3 km grid	Regional Ocean Model System (ROMS); Masson and Fine (2012)
Bathymetry (Bathy)	m	British Columbia Bathymetric Digital Elevation Model (DEM)	20 m grid	Davies et al. (In press)
Roughness	m	The difference between the maximum and minimum depths of a cell and its eight surrounding cells	20 m grid	Derived from bathymetry using the raster package (Hijmans 2019)
Terrain ruggedness index (TRI)	–	The mean of the absolute differences between the value of a cell and the values of eight surrounding cells	20 m grid	Derived from bathymetry using the raster package (Hijmans 2019)
Vector ruggedness index (VRM)	–	Mean difference between the value of a cell and its neighbours, but accounting for differences related to the local slope of the seafloor	20 m grid	Derived from bathymetry using the raster package (Sappington 2007)
Topographic position index (TPI)	–	The difference between the value of a cell and the mean value of the eight surrounding cells, indicating the site was on a "hill" or in a "valley" relative to its surroundings	20 m grid	Derived from bathymetry using the raster package (Hijmans 2019)
Bathymetric slope	%	Maximum difference between a cell and its eight surrounding neighbours	20 m grid	Derived from bathymetry using the raster package (Hijmans 2019)
Aspect of the slope (Aspect)	degrees	Direction the seafloor slope is facing	20 m grid	Derived from bathymetry using the raster package (Hijmans 2019)
Exposure of site (Fetch)	m	Exposure calculated by the distance from each site to land in directions around the compass at 30 degree intervals	site	Derived from bathymetry layer using the raster package and custom written functions
Calculated exposure	m	Exposure calculated for index sites from 1978-1980	site	Lessard and Campbell (2007)

Variable	Unit	Definition	Original Scale	Source
Substrate type (Substrate)	–	Predicted substrate type (mud, sand, mixed or rock) interpolated to a 20 m by 20 m raster grid	100 m	Gregr and Haggarty (2016)
Depth	m	Mean tide-corrected depth at each site	site	Diver measurements
Slope	%	Maximum difference between depth measurements at quadrats at a site	site	Calculated from diver depth measurements
Estimated exposure	–	Exposure category estimated by diver	site	Estimated by diver
Sunflower Star abundance (*Pycnopodia*)	no. $\cdot m^{-2}$	Number of sunflower stars counted at each site	site	Counted by diver
Sea Otter occupancy with expert opinion (Otter PA)	–	Presence/absence of sea otters at each index site (includes expert opinion for QCS and WCVI regions)	site	See Methods Section 2.2.3
Sea Otter occupancy	–	Presence/absence of sea otters at each index site	site	See Methods Section 2.2.3

Table 6. Correlations between potential explanatory environmental variables for Northern Abalone density, and variance inflation factors (VIF).

Variable	Substrate	Tides	Currents	Salinity	VRM	Bathy	TPI	TRI	Aspect	Fetch	VIF
Substrate	1.00	-0.02	0.05	0.14	0.01	0.07	-0.01	0.10	0.01	-0.03	1.03
Tides	-0.02	1.00	0.67	0.03	-0.09	-0.08	0.00	-0.15	-0.01	0.08	1.92
Currents	0.05	0.67	1.00	-0.01	-0.07	-0.07	-0.02	-0.08	0.00	-0.03	1.87
Salinity	0.14	0.03	-0.01	1.00	-0.12	0.04	-0.02	0.03	0.04	0.08	1.07
VRM	0.01	-0.09	-0.07	-0.12	1.00	0.20	0.05	0.63	0.06	-0.04	1.74
Bathy	0.07	-0.08	-0.07	0.04	0.20	1.00	0.03	0.32	0.09	0.11	1.18
TPI	-0.01	0.00	-0.02	-0.02	0.05	0.03	1.00	0.06	0.00	-0.03	1.01
TRI	0.10	-0.15	-0.08	0.03	0.63	0.32	0.06	1.00	0.03	-0.10	1.93
Aspect	0.01	-0.01	0.00	0.04	0.06	0.09	0.00	0.03	1.00	0.01	1.02
Fetch	-0.03	0.08	-0.03	0.08	-0.04	0.11	-0.03	-0.10	0.01	1.00	1.06

Table 7. Summarized results of generalized additive models used to identify environmental variables for standardizing Northern Abalone densities for total ($\geq$ 20 mm shell length), juveniles (20 mm $\geq$ shell length $<$70 mm), adults ($\geq$ 70 mm shell length) and large adults ($\geq$ 100 mm shell length) for the years 1978-2018 (All) and 2006-2018. An X indicates that the environmental variable was significant (α = 0.05) in the generalized additive model analysis. See Table 5 for environmental variable definitions

Size category	**Years**	**Salinity**	**Tides**	**Otter PA**	**Fetch**	**VRM**	**Currents**	**TRI**	**Depth**	**Substrate**	***Pycno-podia***	**Bathy**	**TPI**	**Aspect**	**Deviance explained**
Northern BC															
Total	All	X			X	X		X							0.44
	2006-2018	X						X							0.23
Juvenile	All	X	X		X	X		X		X					0.5
	2006-2018	X	X		X	X				X					0.35
Adult	All	X	X	X	X							X			0.33
	2006-2018	X													0.16
Large adult	All	X	X		X	X							X		0.35
	2006-2018	X	X						X						0.18
Southern BC															
Total	All			X			X								0.26
	2006-2018			X			X		X		X				0.25
Juvenile	All						X					X		X	0.33
	2006-2018			X			X		X						0.26
Adult	All			X											0.19
	2006-2018										X				0.16
Large adult	All									X					0.27
	2006-2018		X												0.66
	Total occur-rences	8	6	5	5	4	4	3	3	3	2	2	1	1	

8 FIGURES

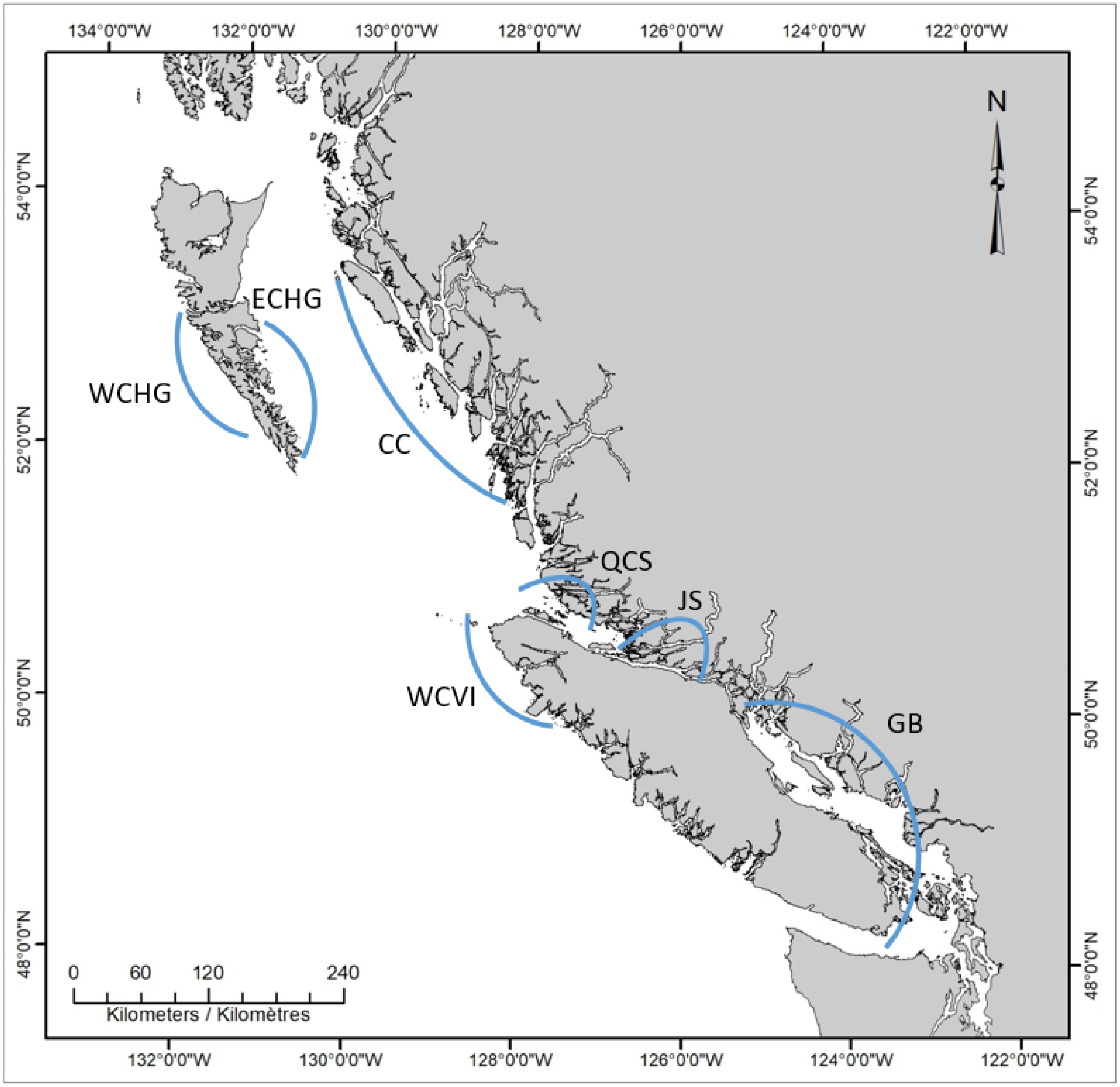


Figure 1. Map of regions surveyed in the Northern Abalone Index Site Surveys in British Columbia. Index site data are available from six regions: East Coast Haida Gwaii (ECHG), West Coast Haida Gwaii (WCHG), Central Coast (CC), Queen Charlotte Strait (QCS), Georgia Basin (GB), and West Coast Vancouver Island (WCVI). Johnstone Strait (JS) was surveyed once in 1986 and alongside the QCS region in 2004, but is no longer surveyed.

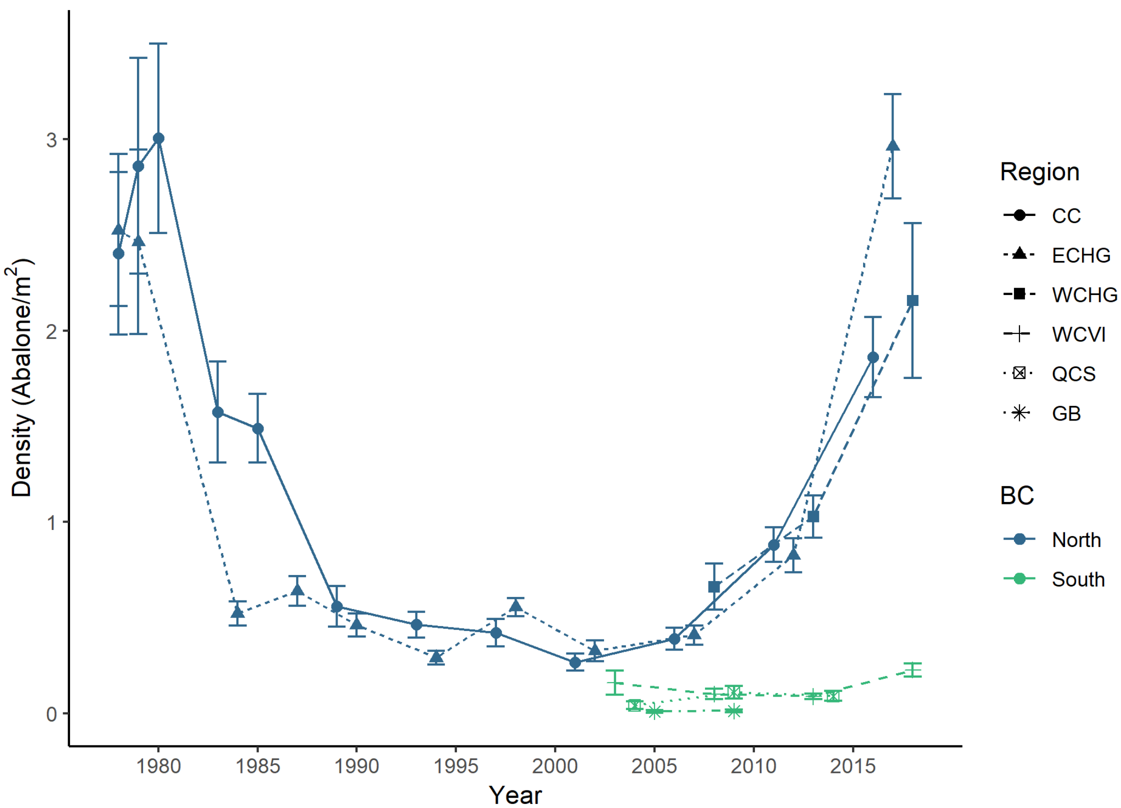


Figure 2. Total Northern Abalone (≥ 20 mm shell length) density trends (mean ± s.e.) by region in British Columbia, illustrating proposed North-South division of data. Index site data are available from six regions: East Coast Haida Gwaii (ECHG), West Coast Haida Gwaii (WCHG), Central Coast (CC), Queen Charlotte Strait (QCS), Georgia Basin (GB), and West Coast Vancouver Island (WCVI).

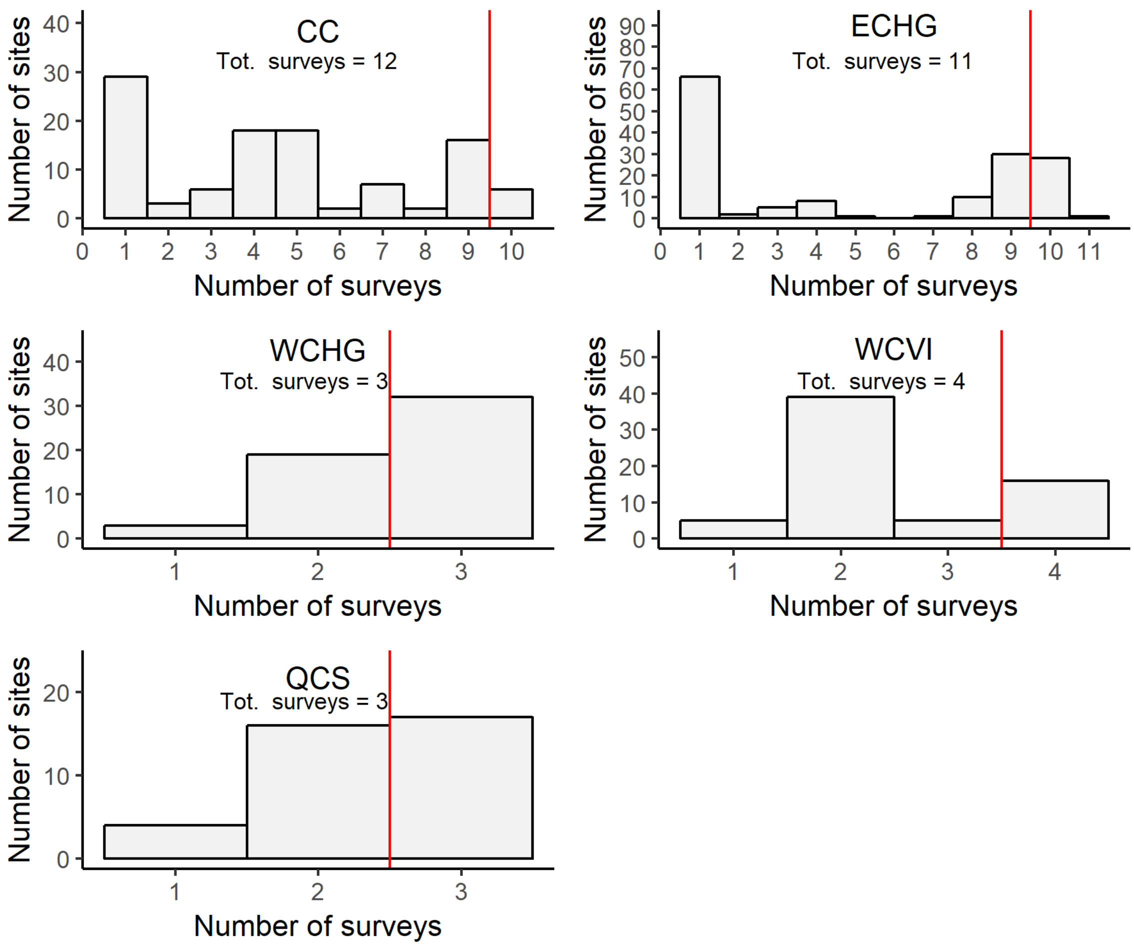


Figure 3. Distribution of repeated sampling of index sites in each region. The number of surveys (x-axis) represents the number of surveys between 1978 and 2018 in which an index site was sampled, up to the total number of surveys in each region (Tot. no. surveys). Red lines represent the cut-off used for the restricted series of index sites; index sites sampled on fewer surveys than this line were discarded in the restricted series. Note that the x-axis limit reflects the maximum number of surveys any index sites were sampled on (for example, for CC, where no site was sampled on all 12 surveys, the x-axis limit is less than the total number of surveys). The GB region was not included as each index sites were only sampled on one survey prior to 2019.

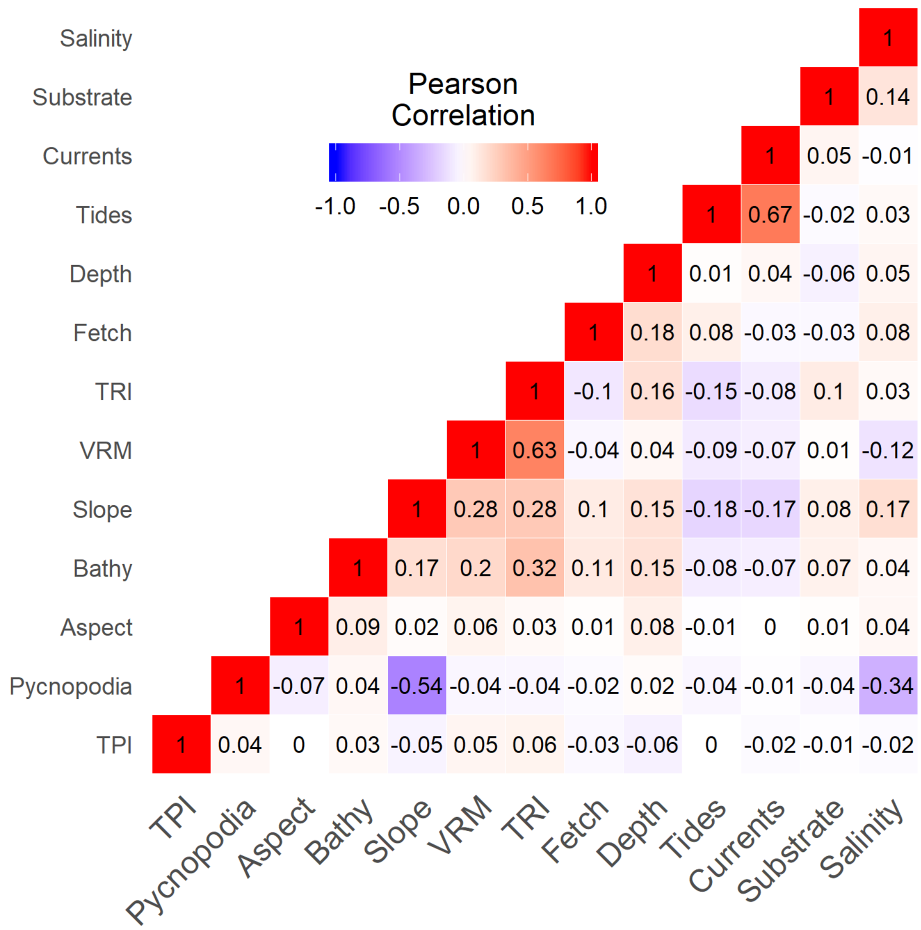


Figure 4. Correlations among potential explanatory environmental variables for standardizing index site densities for Northern Abalone. Environmental variables are defined in Table 5.

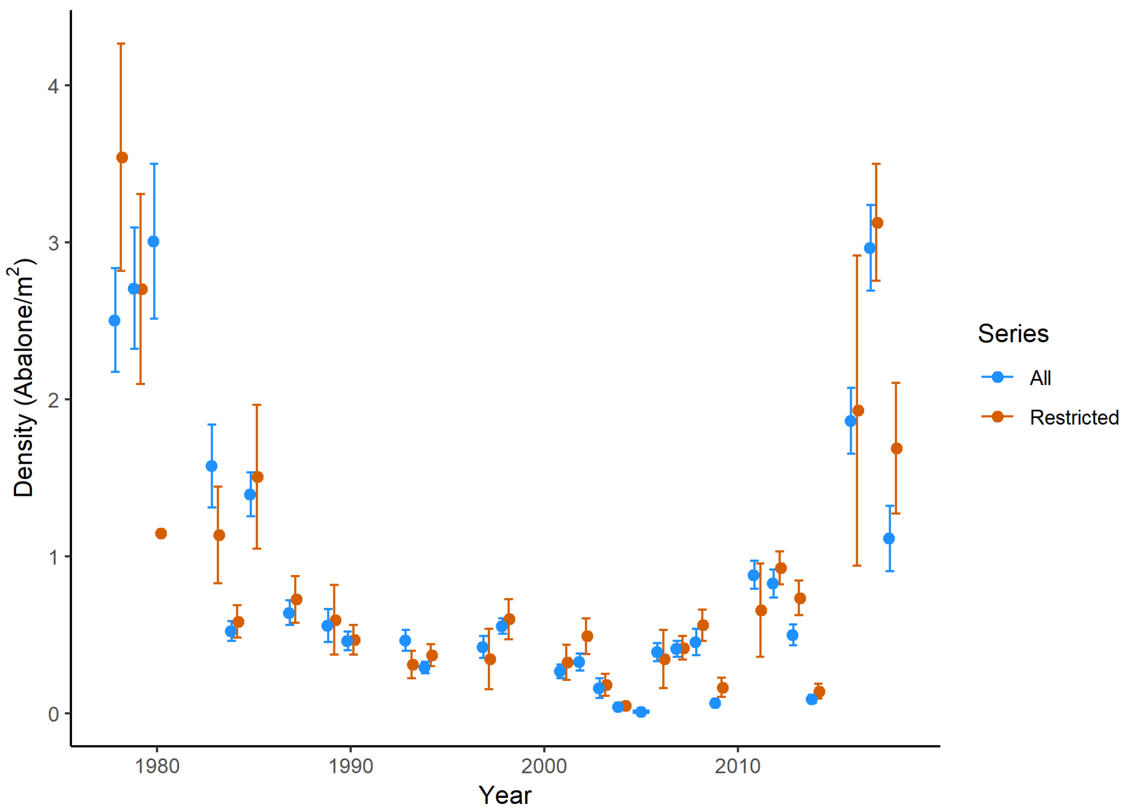


Figure 5. Total Northern Abalone ($\geq$ 20 mm shell length) densities (mean $\pm$ s.e.) over time. The Series legend indicates whether all available sites or a restricted set (those most consistently surveyed over time) are used in density calculations. Note that the differences in mean density between years are a combination of the effect of year and the effect of survey region, as index site data was generally collected in only one survey region per year (see Table 1).

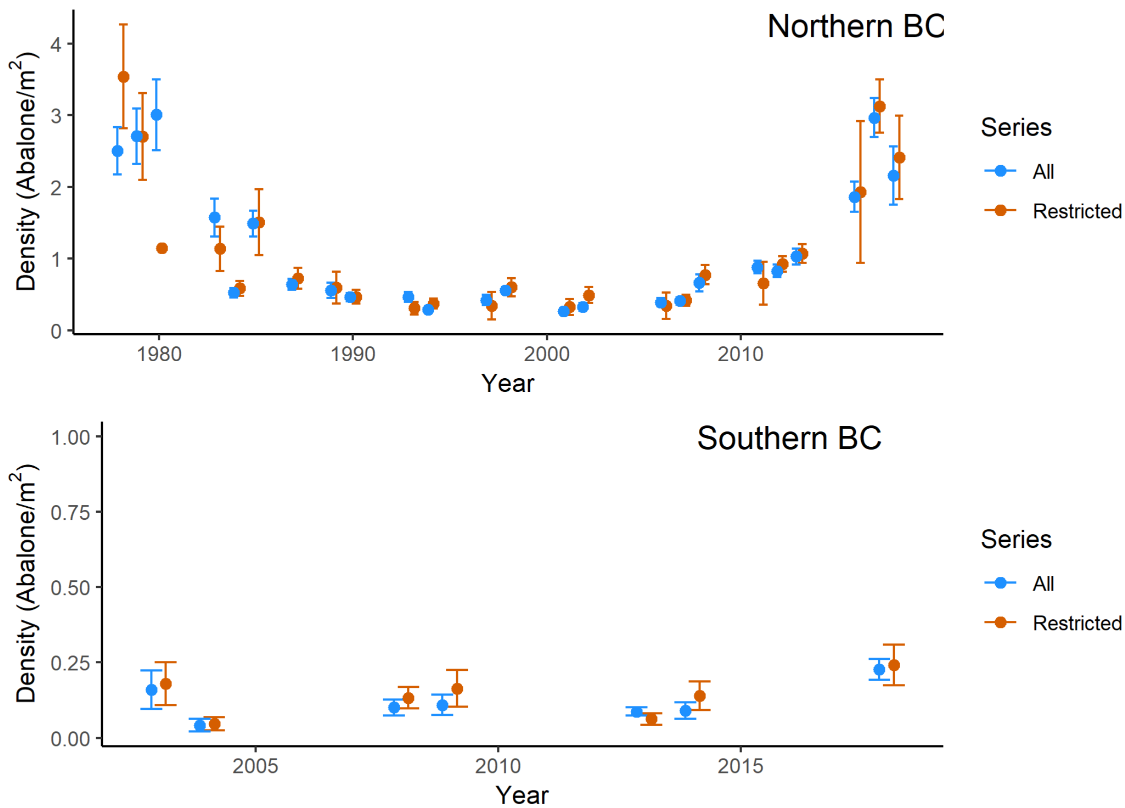


Figure 6. Total Northern Abalone ($\geq$ 20 mm shell length) densities (mean $\pm$ s.e.) over time for Northern BC dataset (upper panel) and Southern BC dataset (lower panel). The Series legend indicates whether all available sites or a restricted set (those most consistently surveyed over time) are used in density calculations. Note that the differences in mean density between years are a combination of the effect of year and the effect of survey region, as index site data were generally collected in only one survey region per year, except for 1978 and 1979 in Northern BC (see Table 1).

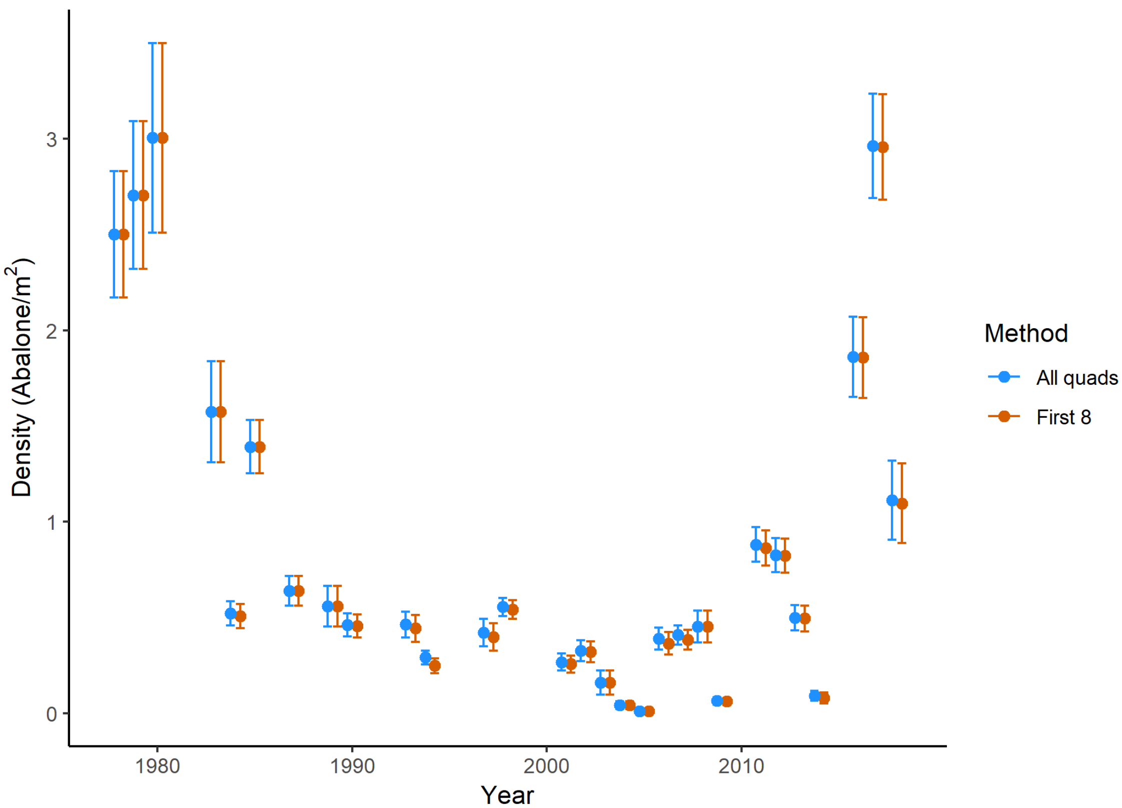


Figure 7. Total Northern Abalone ($\geq$ 20 mm shell length) densities (mean $\pm$ s.e.) at all sites over time. The Method legend indicates whether all quadrats (All quads) or only the first eight quadrats (First 8) are used in density calculations when no Northern Abalone were encountered in the first eight quadrats in a survey. Note that the differences in mean density between years are a combination of the effect of year and the effect of survey region, as index site data was generally collected in only one survey region per year (see Table 1).

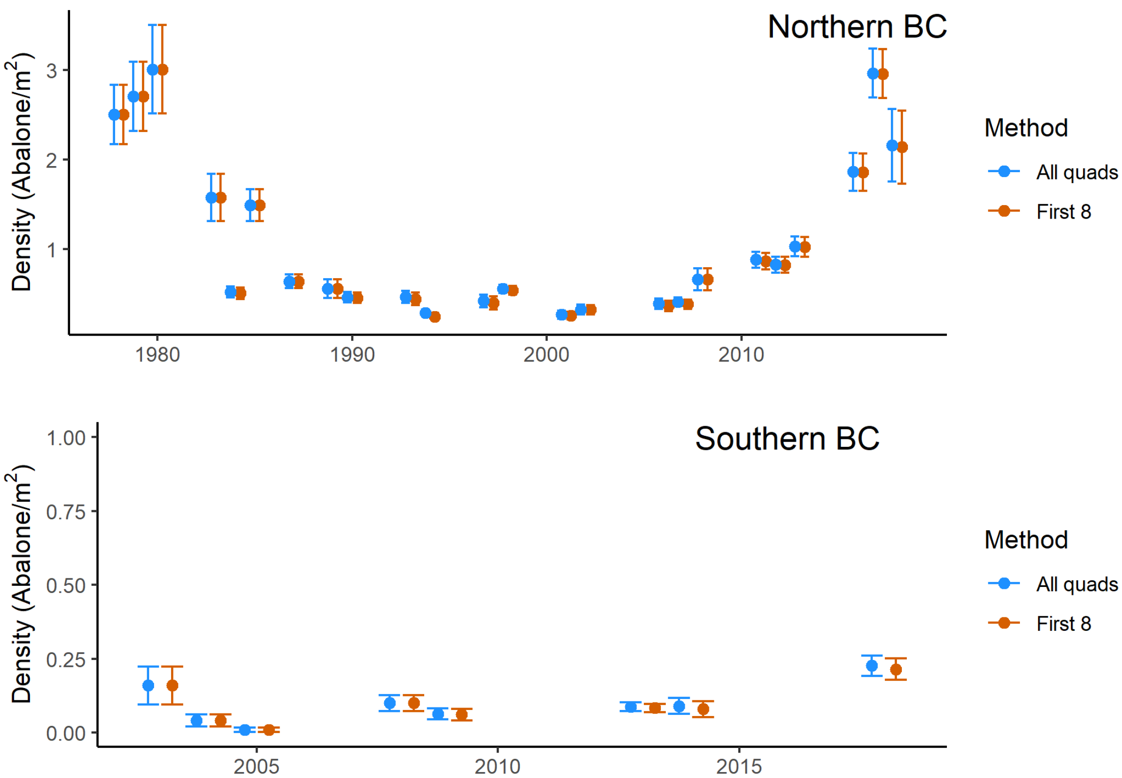


Figure 8. Total Northern Abalone ($\geq$ 20 mm shell length) densities (mean $\pm$ s.e.) at all sites over time for Northern BC dataset (upper panel) and Southern BC dataset (lower panel). The Method legend indicates whether all quadrats (All quads) or only the first eight quadrats (First 8) are used in density calculations when no Northern Abalone were encountered in the first eight quadrats in a survey. Note that the differences in mean density between years are a combination of the effect of year and the effect of survey region, as index site data were generally collected in only one survey region per year, except for 1978 and 1979 in Northern BC (see Table 1).

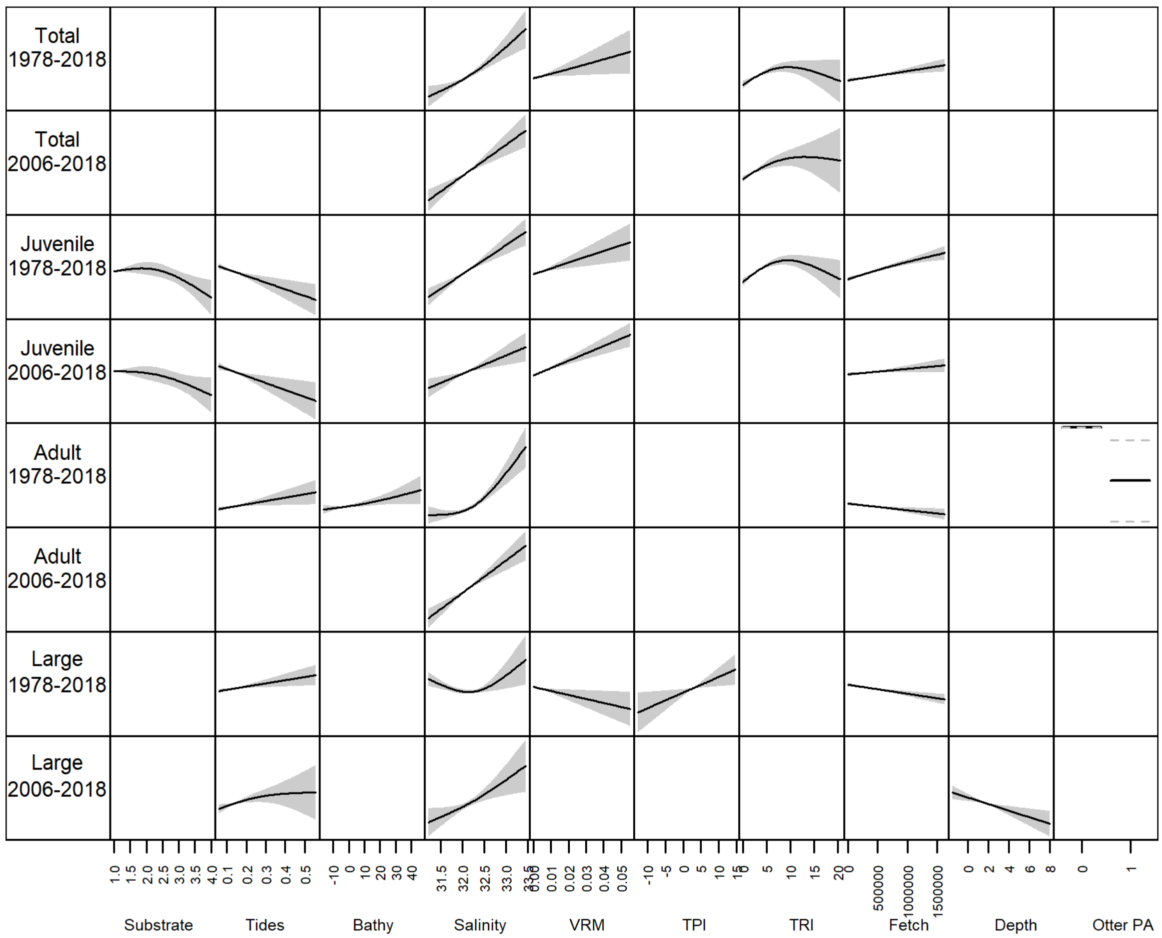


Figure 9. Best-fitting relationships between environmental variables and Northern Abalone densities for total ($\geq$ 20 mm shell length), juveniles ($\geq$ 20 to $<$70 mm shell length), adults ($\geq$ 70 mm shell length) and large adults ($\geq$ 100 mm shell length), for 1978-2018 and for 2006-2018. Data are the Northern BC dataset. Empty plots indicate that the variable was insignificant in the model. Environmental variables are defined in Table 5.

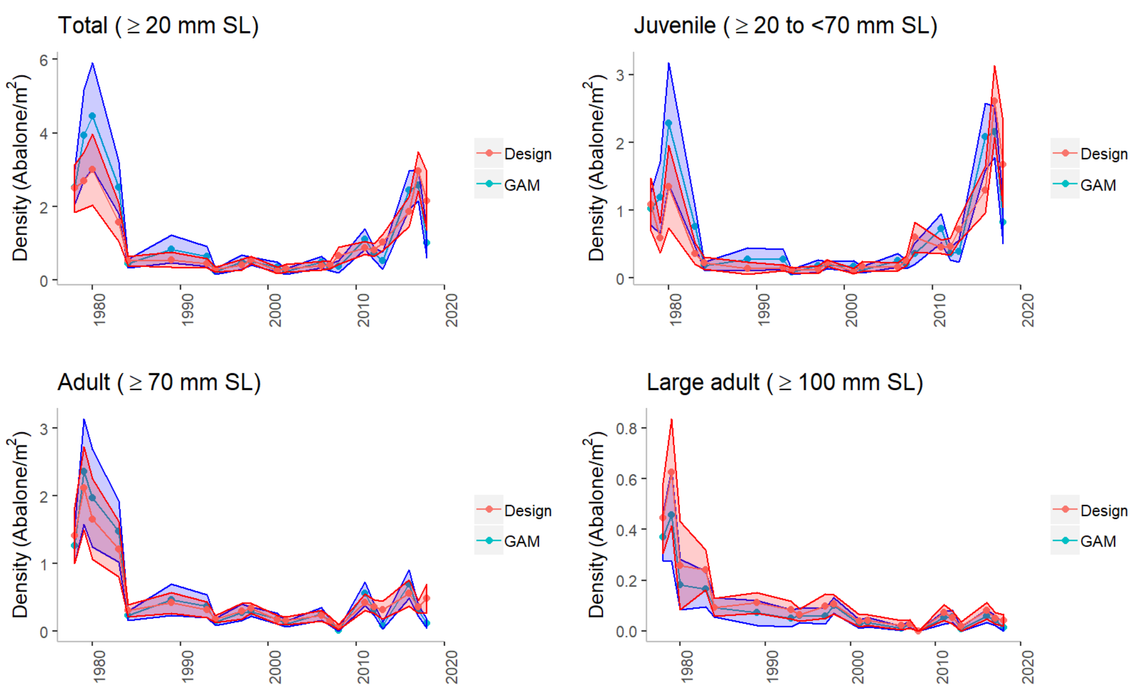


Figure 10. Design-based and model-standardized (GAM) indices of Northern Abalone densities (mean ± 95% CI) for the Northern BC dataset, where SL = shell length. Note that the differences in mean density between years are a combination of the effect of year and the effect of survey region, as only one region was surveyed each year, except in 1978 and 1979 (see Table 1).

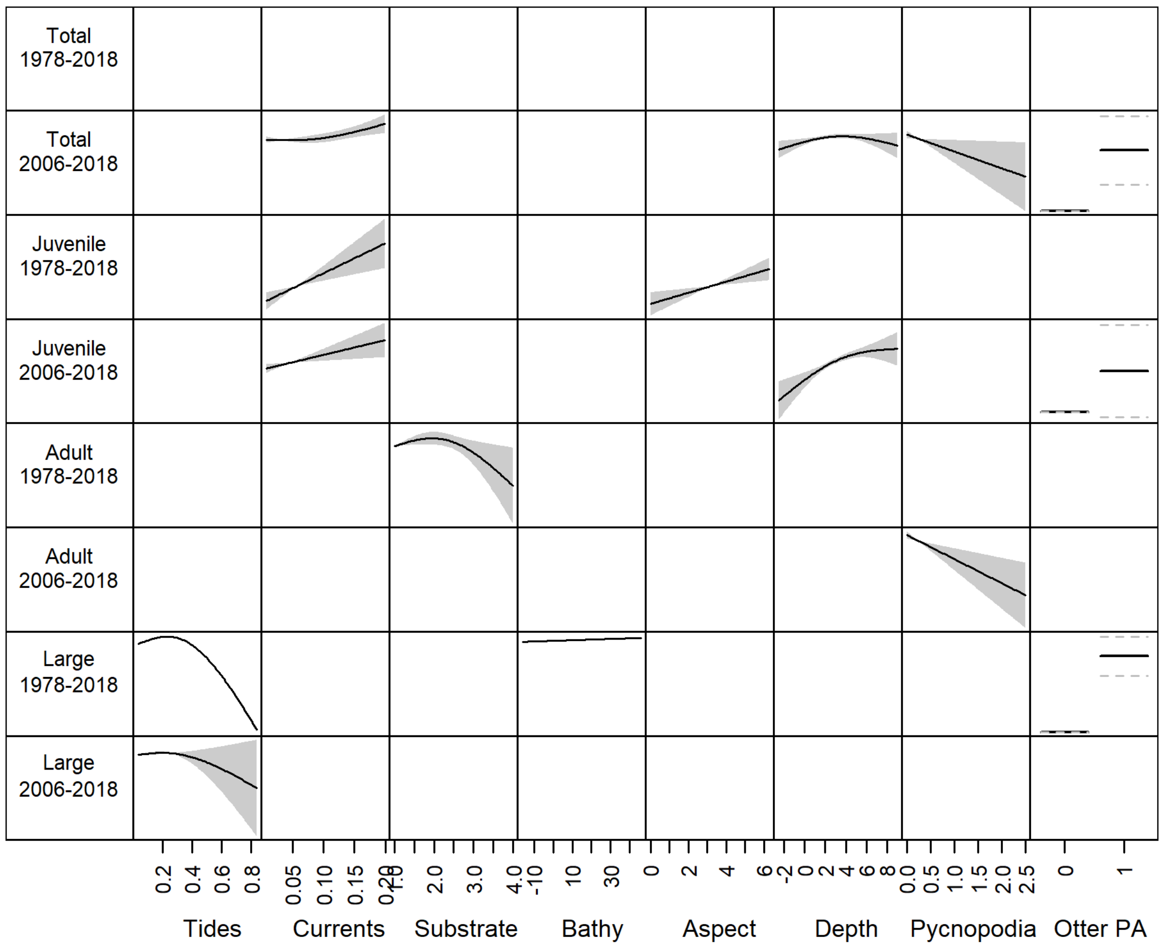


Figure 11. Best-fitting relationships between environmental variables and Northern Abalone densities for total ($\geq$ 20 mm shell length), juveniles ($\geq$ 20 to $<$70 mm shell length), adults ($\geq$ 70 mm shell length) and large adults ($\geq$ 100 mm shell length), for 1978-2018 and for 2006-2018. Data are the Southern BC dataset. Empty plots indicate that the variable was insignificant in the model. Environmental variables are defined in Table 5.

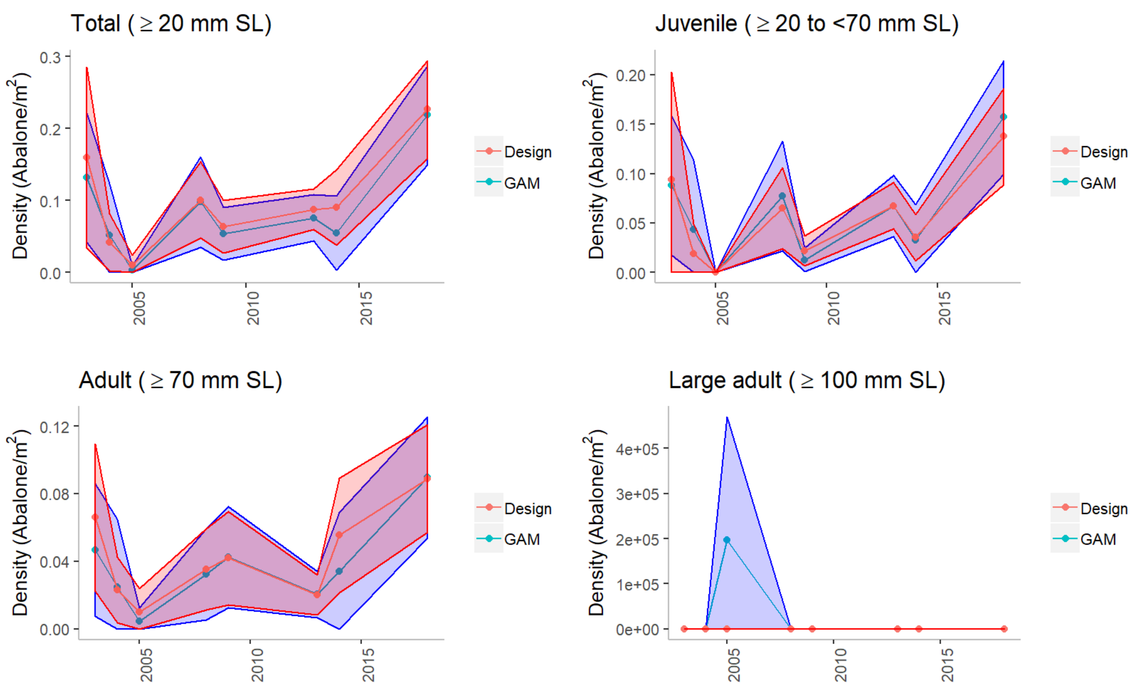


Figure 12. Design-based and model-standardized (GAM) indices of Northern Abalone densities (mean $\pm$ 95% CI) for the Southern BC dataset, where SL = shell length. Note that the differences in mean density between years are a combination of the effect of year and the effect of survey region, as only one region was surveyed each year (see Table 1).

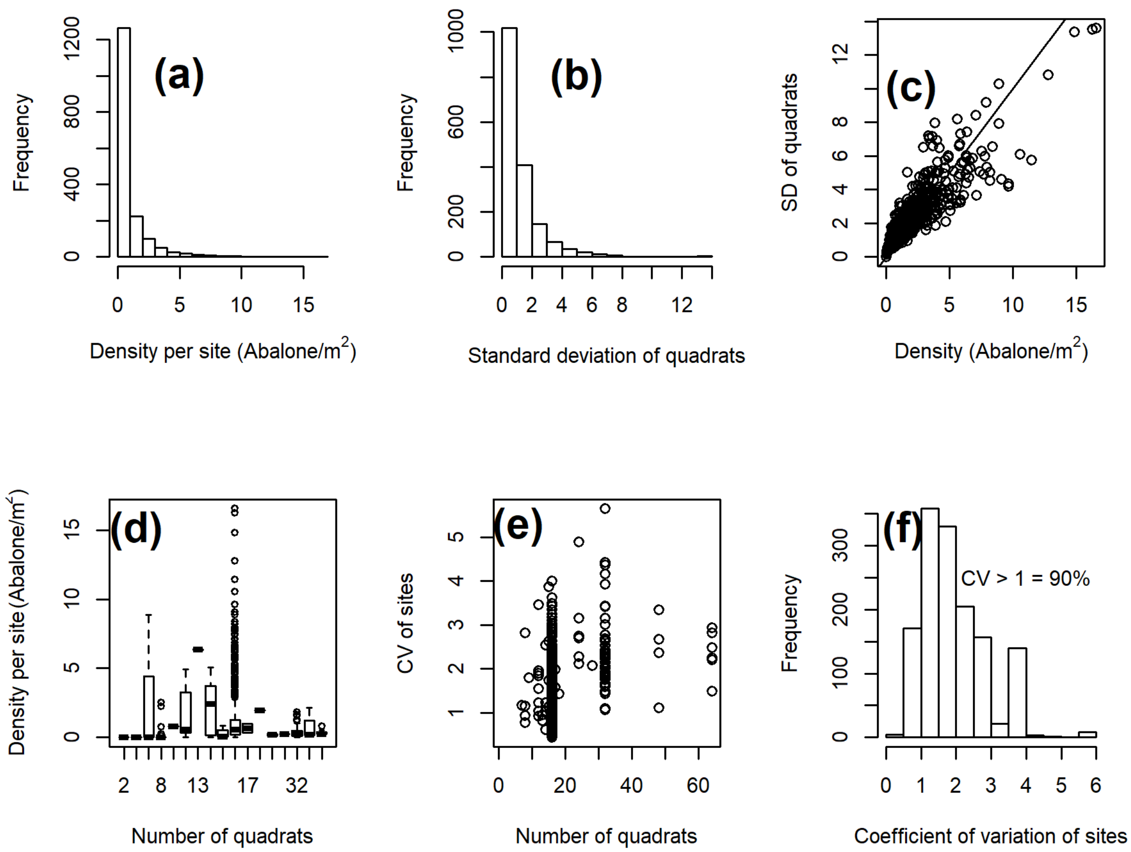


Figure 13. Characteristics of index site and quadrat-level variation in total Northern Abalone ($\geq$ 20 mm shell length) density. Histograms of (a) the density and (b) standard deviations of quadrats across all Northern Abalone index sites, (c) the relationship between density and standard deviation for index sites, (d) the mean density against the number of quadrats at a site, (e) the coefficient of variation (CV) at sites as a function of the number of quadrats sampled per site, and (f) the distribution of coefficient of variation for individual index sites.

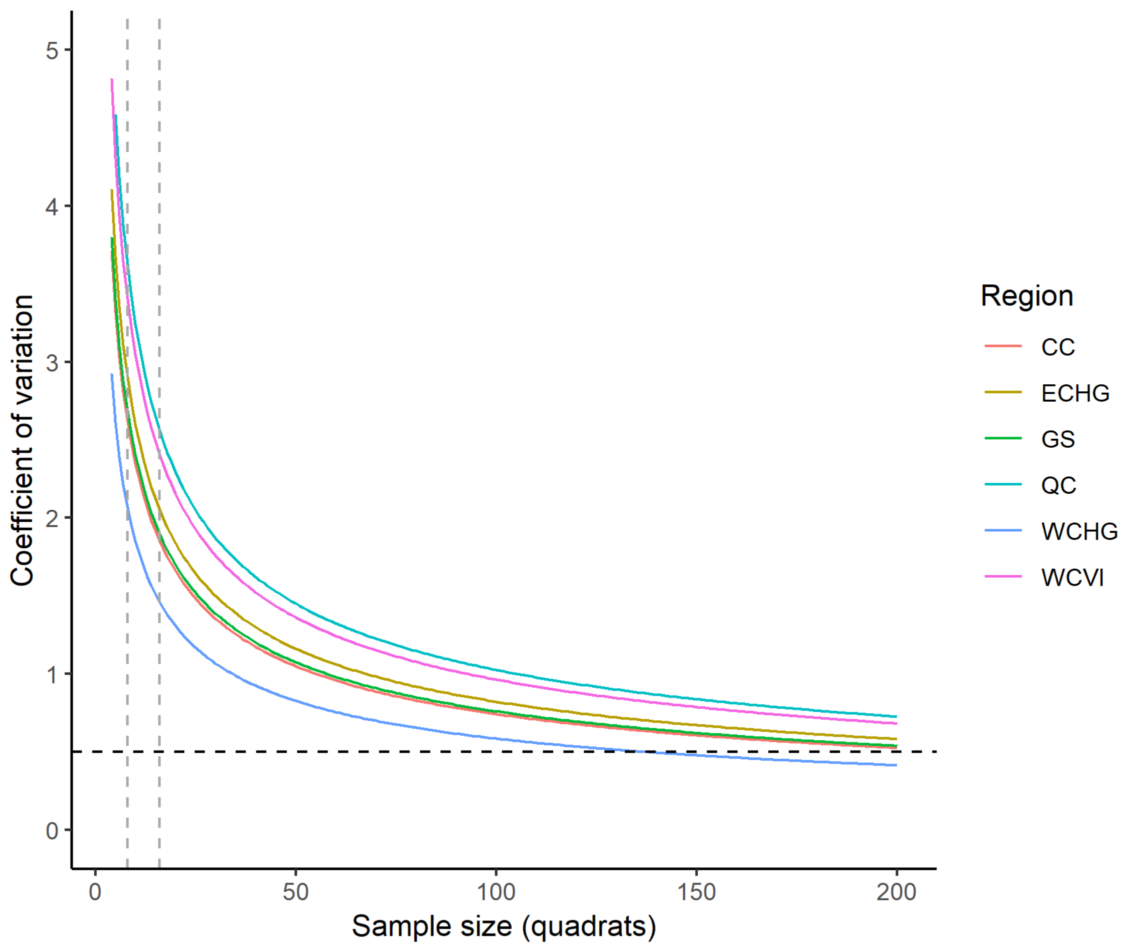


Figure 14. Estimates of the coefficient of variation in average site density of total Northern Abalone (≥ 20 mm shell length), estimated from sample sizes of the number of quadrats (from 3 to 200) using the observed variation in quadrat-level density from each region of Northern Abalone index sites. The two vertical dashed lines are at 8 and 16, the most common number of quadrats sampled during the Northern Abalone Index Site Surveys time series. The horizontal line represents a coefficient of variation of 0.5.

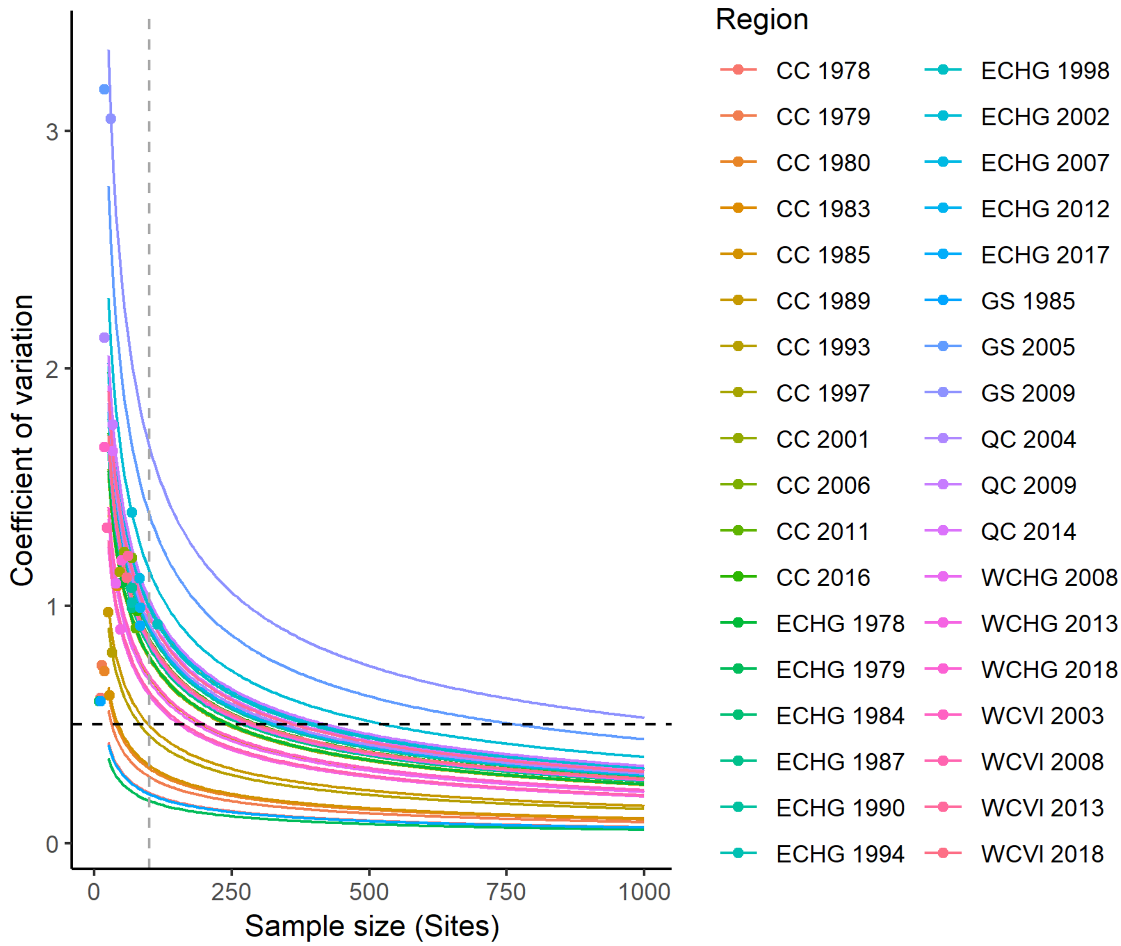
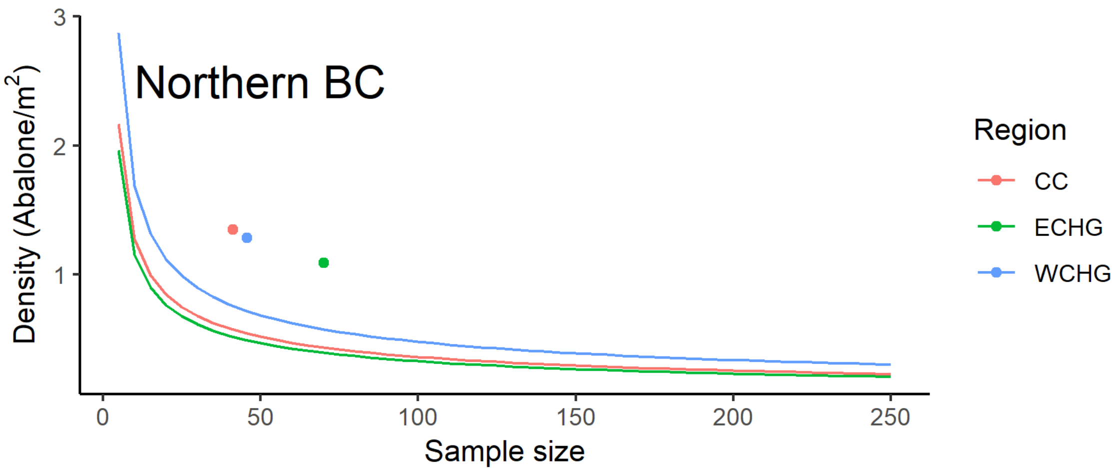


Figure 15. Estimates of the coefficient of variation in average annual density of total Northern Abalone (≥ 20 mm shell length) for each region. These were estimated from varying sample sizes of the number of sites (from 3 to 1000) using the observed variation in site-level density from each region and year of Northern Abalone index sites. The points indicate the observed coefficient of variation around the mean density of total Northern Abalone (≥ 20 mm shell length) for each survey year-region combination. The vertical line represents a sample size of 100 index sites. The horizontal line represents a coefficient of variation of 0.5.



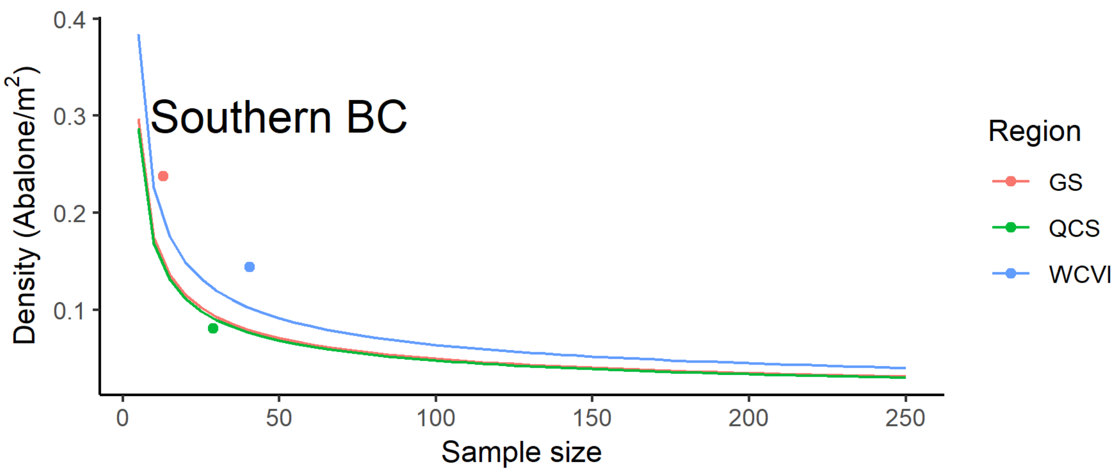


Figure 16. Detectable difference in density of total Northern Abalone (≥ 20 mm shell length) against sample size (number of index sites sampled). Points indicate the mean density of total Northern Abalone (y-axis) and the average number of index sites sampled (x-axis) across the entire time series (1978-2018) for each region.

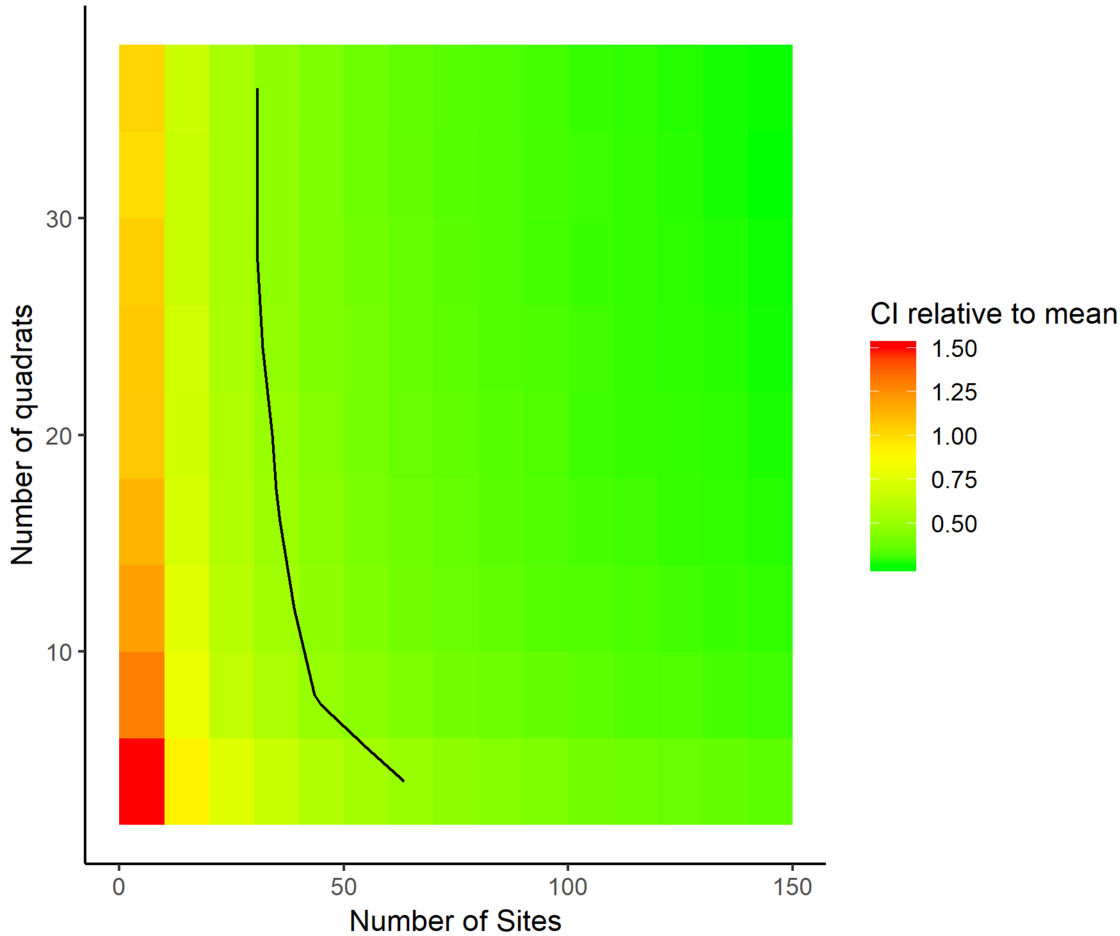


Figure 17. Simulation exercise estimating the 95% confidence interval width relative to the calculated mean density of total Northern Abalone ($\geq$ 20 mm shell length), under a range of sample sizes for quadrats (0-40) and sites (0-150). The analysis resampled the pooled data across years and regions. The black line indicates the level of sampling where the 95% confidence interval width would be half of the mean density.

APPENDIX A DATA CONTINUITY IN THE NORTHERN ABALONE DATABASE

The Breen Survey Method for surveying Northern Abalone has evolved since it was first applied in 1978. In preparation for the upcoming reassessment of Northern Abalone status in Canada by COSEWIC, we reviewed the available data in the DFO Northern Abalone database, including the available environmental variables. We examined the consistency of data collection and recording over the four decades of surveys for fifteen variables. Six variables were at the level of the index site sampling unit (site-level) and nine were at the quadrat-level (Table A.1). Observations of variables made at the outset of the surveys were not always continued and the addition of new variables was common across the survey time series. Advances in the understanding of Northern Abalone biology, application of new technology, and a shift in focus toward Northern Abalone recovery are examples of drivers of change in the observations made. Adoption of changes to the variables observed tended to cascade through the six regions such that full adoption of the change would take five years to apply uniformly. The treatment of these fifteen variables over time is documented in Tables A.1-A.14, except for the variable ‘Cryptic Northern Abalone observations’ which is found in Table 3.

A situation that was more difficult to discern in the data was when interpretation of the protocols for survey data collection or electronic data capture changed. For a survey time series as long as the Northern Abalone Index Site Surveys, the head scientist at-sea changed numerous times as did dive participants. Maintaining consistency in interpretation of the protocols from one survey to the next could be challenging when participants were new to the survey or the electronic data capture process. This impacted the data for the site-level algae and substrate variables over time.

Another situation relating to changes in survey protocols, or interpretations thereof, with unknown implications for Northern Abalone density estimates is the attempt to maintain consistent detection rates by removing algae. In practice, algal removal from surveyed quadrats is not consistent across years, as divers exercise some discretion in effective search methods under different conditions. For example, divers are often able to survey below the subsurface canopy created by the stipitate (*Pterygophora californica*). In rough conditions, the stipes serve as useful handholds and may accordingly benefit search efficiency; however, occasionally the stipes are so dense as to prevent effective searching. Not all surveys mention the removal of algae, and those that do utilize inconsistent phrasing. For example Boutillier et al. (1984) refers to the removal of all large kelp plants, whereas Carolsfeld et al. (1988) and Farlinger et al. (1991) suggest that only those kelp plants that obscured vision were removed. There is also a shift in terminology between kelp (Boutillier et al. 1984; Carolsfeld et al. 1988; Farlinger et al. 1991; Atkins et al. 2004; Davies et al. 2006; Lessard et al. 2007b; Hankewich and Lessard 2008; Hankewich et al. 2008), vegetation (Winther et al. 1995; Campbell and Cripps 1998; Campbell 2000; Atkins and Lessard 2004; Egli and Lessard 2011; Lessard and Egli 2011) and algae (Curtis and Zhang 2018).

Table A.1. Summary of environmental variables examined for continuity over time, where observations apply to either the sampling unit (site-level) or a subset of the sampling unit (quadrat-level).

Variable	Observation level	Description [Database Table]
Slope	Site	Slope of site as recorded by divers [Headers]
Exposure	Site	Exposure codes: 0-extreme shelter; 1-minimal sea movement; 2-well sheltered; 3-occasional current; 4-moderate exposure; 5-strong tidal flow; 6-high tide surge only; 7-ground swell normal; 8-high exposure; -99-exposure not recorded [Headers]
Minimum/Maximum Depth (corrected for tide)	Site	Minimum/maximum depth in meters, corrected for tide [Headers]
Substrate	Site	Three fields for recording substrate codes for shallow, deeper and deepest substrates: 0-wood; 1-bedrock, smooth without crevices; 2-bedrock with crevices; 3-boulders, bigger than a basketball; 4-cobble, between 3 inches and basketball size; 5-gravel, between 3/4 inch and 3 inch; 6-pea gravel, between 1/8 inch and 3/4 inch; 7-sand; 8-shell; 9-mud; 10-crushed shell; 11-whole shell [Site Descriptions]
Algae Species and Percent Cover (by category)	Site	14 fields for recording the primary and secondary algae species in 4 categories (canopy, understory, turf and bottom) with the associated percent cover [Site Descriptions]
Species Relative Abundance	Site	Three fields for recording the relative abundance of Northern Abalone, Sunflower Star and sea urchins: N-none; S-single; F-few (2-10); M-many (11-100); A-abundant (>100) [Site Descriptions]
Depth (corrected for tide)	Quadrat	Quadrat depth in meters, corrected for tide [Density]
Substrate	Quadrat	Three fields for recording 1st, 2nd and 3rd most abundant substrate codes: 0-wood; 1-bedrock, smooth without crevices; 2-bedrock with crevices; 3-boulders, bigger than a basketball; 4-cobble, between 3 inches and basketball size; 5-gravel, between 3/4 inch and 3 inch; 6-pea gravel, between 1/8 inch and 3/4 inch; 7-sand; 8-shell; 9-mud; 10-crushed shell; 11-whole shell [Density]
Substrate Category	Quadrat	Grouping of multiple substrate codes into one of five categories: 1-Bedrock (hard and/or smooth); 2-Hard, complex boulder; 3-Cobble; 4-Mixed hard/soft with hard terminate; 5-Mainly soft [Density]
Percent Substrate	Quadrat	Three fields for recording percent of 1st, 2nd and 3rd most abundant substrates [Density]
Predator ID/Count	Quadrat	Four fields for recording 1st and 2nd most abundant predator species identification and counts [Density]
Algae Species and Percent Cover	Quadrat	Four fields for recording 1st, 2nd and 3rd most abundant algae species and associated percentage cover [Density]
Urchin Species/Count	Quadrat	Three fields for recording counts of Green Sea Urchin, Purple Sea Urchin and Red Sea Urchin [Density]

Variable	Observation level	Description [Database Table]
Algae Species and Percent Cover (by categories)	Quadrat	19 fields for recording algae cover in four categories (canopy, understory, turf, encrusting and drift). Up to two canopy species, ten understory species and 6 turf species may be recorded. Encrusting is not identified by species. Percent by category represents the total of all species within the category [Habitat]
Cryptic Northern Abalone observations	Quadrat	Two fields for recording counts of cryptic abalone for those years in which cryptic searches were conducted [Density]

Table A.2. Treatment of reporting the site-level variable 'Slope' over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions. In 2001, quadrat-level observations of depth (see Table A.8) began to be recorded allowing for derived site-level slope values.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		Y	Y				
1979		Y	Y				
1980			Y				
1981	NS						
1982					N		
1983			Y				
1984		Y			N		
1985			Y		N		
1986							
1987		Y					
1988	NS						
1989			Y				
1990		Y					
1991	NS						
1992	NS						
1993			Y				
1994		Y					
1995	NS						
1996	NS						
1997			Y				
1998		Y					
1999	NS						
2000	NS						
2001			N				
2002		Y					
2003						N	
2004				N			
2005					N		
2006			N				
2007		N					
2008						N	N
2009				N	N		
2010	NS						
2011			N				
2012		N					
2013						N	N
2014				N			
2015	NS						
2016			N				
2017							N
2018						N	N

Table A.3. Treatment of reporting the site-level variable 'Exposure' over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	Survey	ECHG	CC	QCS	GB	WCVI	WCHG
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					Y		
1983			Y				
1984		Y					
1985			Y		Y		
1986					Y		
1987		Y					
1988	NS						
1989			Y				
1990		Y					
1991	NS						
1992	NS						
1993			Y				
1994		Y					
1995	NS						
1996	NS						
1997			Y				
1998		Y					
1999	NS						
2000	NS						
2001			N				
2002		Y					
2003						N	
2004				N			
2005					N		
2006			N				
2007		N					
2008						N	N
2009				N	N		
2010	NS						
2011			N				
2012		N					
2013						N	N
2014				N			
2015	NS						
2016			N				
2017		N					
2018						N	N

Table A.4. Treatment of reporting the site-level variables 'Minimum and Maximum Depth (corrected for tide)' over time, where Y indicates sufficient information was recorded to allow for a calculation to be made, N indicates insufficient information recorded and NS indicates no survey was conducted in any of the six regions. Beginning in 2001, quadrat-level observations of depth coupled with tide height values also informed site-level minimum and maximum depths (see Table A.8).

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N			N		
1985			N		N		
1986							
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			Y				
2002		Y					
2003						Y	
2004							
2005					Y		
2006			Y				
2007		Y					
2008						Y	Y
2009				Y	Y		
2010	NS						
2011			Y				
2012		Y					
2013						Y	Y
2014				Y			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

Table A.5. Treatment of reporting the site-level variable 'Substrate' over time, where Y1 and Y2 indicate observation recorded through 1 of 2 methods and NS indicates no survey was conducted in any of the six regions. The first method (Y1) resulted in a single substrate code being recorded in a single field in the database (i.e. Substrate1, Substrate2, Substrate3, each with a single substrate code). The second method (Y2) resulted in multiple values being recorded in a single field in the database (i.e. Substrate1 field containing multiple substrate codes variously separated by spaces, commas, or slashes).

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		Y1	Y1				
1979		Y1	Y1				
1980			Y1				
1981	NS						
1982					Y1		
1983			Y1				
1984		Y1					
1985			Y1		Y1		
1986					Y1		
1987		Y1					
1988	NS						
1989			Y1				
1990		Y1					
1991	NS						
1992	NS						
1993			Y1				
1994		Y1					
1995	NS						
1996	NS						
1997			Y1				
1998		Y1					
1999	NS						
2000	NS						
2001			Y1				
2002		Y1					
2003						Y1	
2004				Y2			
2005					Y1		
2006			Y2				
2007		Y1					
2008						Y2	Y2
2009				Y2	Y2		
2010	NS						
2011			Y2				
2012		Y2					
2013						Y2	Y2
2014				Y1			
2015	NS						
2016			Y1				
2017		Y1					
2018						Y2	Y2

Table A.6. Treatment of reporting the site-level variables 'Algae Species and Percent Cover (by category)' (species by categories: Canopy, Understory, Turf, Encrusting; percent cover) over time, where Y1, Y2, and Y3 indicate observation recorded through 1 of 3 methods and NS indicates no survey was conducted in any of the six regions. If more than one species of algae was recorded, either a percent cover was assigned for each species in methods Y1 and Y2 (i.e. Canopy1Percent and Canopy2Percent would each have a value if two canopy species were identified) or the combined percent cover of all species in the category (i.e. Canopy) was entered in the Canopy1Percent field only in method Y3. If no algae species were observed, the percent cover was electronically captured as zero (0) in methods Y1 and Y3 or as Null (blank) in method Y2.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		Y1	Y1				
1979		Y1	Y1				
1980			Y1				
1981	NS						
1982					Y1		
1983			Y1				
1984		Y1					
1985			Y1		Y1		
1986					Y1		
1987		Y2					
1988	NS						
1989			Y2				
1990		Y2					
1991	NS						
1992	NS						
1993			Y2				
1994		Y2					
1995	NS						
1996	NS						
1997			Y1				
1998		Y1					
1999	NS						
2000	NS						
2001			Y2				
2002		Y2					
2003						Y1	
2004				Y1			
2005					Y1		
2006			Y1				
2007		Y3					
2008						Y3	Y3
2009				Y3	Y3		
2010	NS						
2011			Y3				
2012		Y3					
2013						Y3	Y3
2014				Y3			
2015	NS						
2016			Y3				
2017		Y3					
2018						Y3	Y3

Table A.7. Treatment of reporting the site-level variable 'Species Relative Abundance' of Northern Abalone, sea urchins and sunflower stars over time, where Y indicates observation was recorded, Y* indicates observation restricted to sea urchin relative abundance and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		Y*	Y*				
1979		Y*	Y*				
1980			Y*				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						Y	
2004				Y			
2005					Y		
2006			Y				
2007		Y					
2008						Y	Y
2009				Y	Y		
2010	NS						
2011			Y				
2012		Y					
2013						Y	Y
2014				Y			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

Table A.8. Treatment of reporting the quadrat-level variable 'Depth (corrected for tide)' over time, where Y indicates sufficient information was recorded to allow for a calculation to be made, N indicates information was not recorded and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			Y				
2002		Y					
2003						Y	
2004				N			
2005					Y		
2006			Y				
2007		Y					
2008						Y	Y
2009				Y	Y		
2010	NS						
2011			Y				
2012		Y					
2013						Y	Y
2014				Y			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

Table A.9. Treatment of reporting the quadrat-level variables ’Substrate’ and ’Substrate Category’ over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						Y	
2004				Y			
2005					Y		
2006			Y				
2007		Y					
2008						Y	Y
2009				Y	Y		
2010	NS						
2011			Y				
2012		Y					
2013						Y	Y
2014				Y			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

Table A.10. Treatment of reporting the quadrat-level variable 'Percent Substrate' over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions. Prior to the addition of this variable in 2016 only the substrate type was recorded (see Table A.9).

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						N	
2004				N			
2005					N		
2006			N				
2007		N					
2008						N	N
2009				N	N		
2010	NS						
2011			N				
2012		N					
2013						N	N
2014				N			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

Table A.11. Treatment of reporting the quadrat-level variables ’Predator ID’ and ’Predator Count’ over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						N	
2004				N			
2005					N		
2006			Y				
2007		Y					
2008						Y	Y
2009				Y	Y		
2010	NS						
2011			Y				
2012		Y					
2013						Y	Y
2014				Y			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

Table A.12. Treatment of reporting the quadrat-level variables 'Algae Species and Percent Cover' over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions. These observations were replaced in 2006 by a more extensive review of algae species and percent cover (see Table A.14).

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						Y	
2004				Y			
2005					Y		
2006			N				
2007		N					
2008						N	N
2009				N	N		
2010	NS						
2011			N				
2012		N					
2013						N	N
2014				N			
2015	NS						
2016			N				
2017		N					
2018						N	N

Table A.13. Treatment of reporting the quadrat-level variables 'Urchin Species' and 'Urchin Count' over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions. Prior to the addition of this variable in 2017, sea urchin counts were not split by species (see Table A.7).

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						N	
2004				N			
2005					N		
2006			N				
2007		N					
2008						N	N
2009				N	N		
2010	NS						
2011			N				
2012		N					
2013						N	N
2014				N			
2015	NS						
2016			N				
2017		Y					
2018						Y	Y

Table A.14. Treatment of reporting the quadrat-level variables ’Algae Species and Percent Cover (by categories)’ (species by categories: Canopy, Understory, Turf, Encrusting; percent cover) over time, where Y indicates observations recorded, N indicates observations not recorded and NS indicates no survey was conducted in any of the six regions.

		Region					
Year	**Survey**	**ECHG**	**CC**	**QCS**	**GB**	**WCVI**	**WCHG**
1978		N	N				
1979		N	N				
1980			N				
1981	NS						
1982					N		
1983			N				
1984		N					
1985			N		N		
1986					N		
1987		N					
1988	NS						
1989			N				
1990		N					
1991	NS						
1992	NS						
1993			N				
1994		N					
1995	NS						
1996	NS						
1997			N				
1998		N					
1999	NS						
2000	NS						
2001			N				
2002		N					
2003						N	
2004				N			
2005					N		
2006			Y				
2007		Y					
2008						Y	Y
2009				Y	Y		
2010	NS						
2011			Y				
2012		Y					
2013						Y	Y
2014				Y			
2015	NS						
2016			Y				
2017		Y					
2018						Y	Y

APPENDIX B GENERALIZED ADDITIVE MODEL RESULTS, RAW DATA PLOTS OF ENVIRONMENTAL VARIABLES AND NORTHERN ABALONE DENSITIES, AND MODEL DIAGNOSTICS

Table B.1. Best-fitting generalized additive model for predicting total Northern Abalone ($\geq$ 20 mm shell length) density using environmental variables in the Northern BC dataset in 1978-2018.

Term	df/edf	F	p-value
Year	20	45.28	<0.0001
Salinity	1.689	16.145	<0.0001
VRM	1.052	4.357	0.02885
TRI	1.906	9.202	0.00024
Fetch	1.004	12.783	0.00036
residual	1060.349		
GCV	1276.0613		
Deviance explained	43.8%		

Table B.2. Best-fitting generalized additive model for predicting total Northern Abalone ($\geq$ 20 mm shell length) density using environmental variables in the Northern BC dataset in 2006-2018.

Term	df/edf	F	p-value
Year	8	10.82	<0.0001
Salinity	1.001	26.019	<0.0001
TRI	1.751	8.717	0.00133
residual	313.249		
GCV	336.4897		
Deviance explained	22.7%		

Table B.3. Best-fitting generalized additive model for predicting juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) density using environmental variables in the Northern BC dataset in 1978-2018.

Term	df/edf	F	p-value
Year	20	45.93	<0.0001
Substrate	1.84	3.923	0.01446
Tides	1	13.163	3e-04
Salinity	1	34.813	<0.0001
VRM	1.001	10.177	0.00146
TRI	1.95	16.198	<0.0001
Fetch	1.314	34.607	<0.0001
residual	1057.895		
GCV	897.7814		
Deviance explained	49.7%		

Table B.4. Best-fitting generalized additive model for predicting juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) density using environmental variables in the Northern BC dataset in 2006-2018.

Term	**df/edf**	**F**	**p-value**
Year	8	12.19	<0.0001
Substrate	1.608	3.077	0.03081
Tides	1	9.737	0.002
Salinity	1	11.792	0.00069
VRM	1	39.756	<0.0001
Fetch	1	3.941	0.04812
residual	271.392		
GCV	198.3155		
Deviance explained	34.9%		

Table B.5. Best-fitting generalized additive model for predicting adult Northern Abalone ($\geq$ 70 mm shell length) density using environmental variables in the Northern BC dataset in 1978-2018.

Term	**df/edf**	**F**	**p-value**
Otter.PA	1	6.94	0.00857
Year	20	28.45	<0.0001
Tides	1.004	5.378	0.02053
Salinity	1.938	17.959	<0.0001
Bathy	1.261	3.932	0.02197
Fetch	1	8.302	0.00403
residual	1059.797		
GCV	846.2838		
Deviance explained	32.8%		

Table B.6. Best-fitting generalized additive model for predicting adult Northern Abalone ($\geq$ 70 mm shell length) density using environmental variables in the Northern BC dataset in 2006-2018.

Term	**df/edf**	**F**	**p-value**
Year	8	8.41	<0.0001
Salinity	1.001	35.434	<0.0001
residual	314.999		
GCV	193.7612		
Deviance explained	15.8%		

Table B.7. Best-fitting generalized additive model for predicting large Northern Abalone ($\geq$ 100 mm shell length) density using environmental variables in the Northern BC dataset in 1978-2018.

Term	**df/edf**	**F**	**p-value**
Year	1	0	0.99837
Tides	1	6.812	0.00917
Salinity	1.915	6.217	0.00172
VRM	1	5.839	0.01584
TPI	1.003	5.988	0.01459
Fetch	1	17.636	3e-05
residual	1060.081		
GCV	391.831		
Deviance explained	34.8%		

Table B.8. Best-fitting generalized additive model for predicting large Northern Abalone ($\geq$ 100 mm shell length) density using environmental variables in the Northern BC dataset in 2006-2018.

Term	**df/edf**	**F**	**p-value**
Year	1	0	0.99911
Tides	1.601	3.859	0.04774
Salinity	1.437	5.85	0.00682
Depth	1.001	10.37	0.00142
residual	294.962		
GCV	75.7063		
Deviance explained	17.9%		

Table B.9. Best-fitting generalized additive model for predicting total Northern Abalone ($\geq$ 20 mm shell length) density using environmental variables in the Southern BC dataset in 1978-2018.

Term	**df/edf**	**F**	**p-value**
Year	7	6.16	<0.0001
Salinity	1	11.263	0.00096
residual	179		
GCV	57.1367		
Deviance explained	25.3%		

Table B.10. Best-fitting generalized additive model for predicting combined Northern Abalone ($\geq$ 20 mm shell length) density using environmental variables in the Southern BC dataset in 2006-2018.

Term	df/edf	F	p-value
Otter.PA	1	12.6	0.00056
Year	4	1.05	0.3844
Currents	1.742	4.305	0.01016
Depth	1.843	3.621	0.04478
Pycnopodia	1	4.844	0.02968
residual	116.415		
GCV	25.2184		
Deviance explained	25.4%		

Table B.11. Best-fitting generalized additive model for predicting juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) density using environmental variables in the Southern BC dataset in 1978-2018.

Term	df/edf	F	p-value
Year	1	0	0.9997
Currents	1	11.984	0.00067
Aspect	1	9.295	0.00264
residual	178		
GCV	33.4544		
Deviance explained	30.2%		

Table B.12. Best-fitting generalized additive model for predicting juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) density using environmental variables in the Southern BC dataset in 2006-2018.

Term	df/edf	F	p-value
Otter.PA	1	3.17	0.07625
Year	4	8	<0.0001
Currents	1	6.962	0.00891
Depth	1.777	9.541	7e-05
residual	221.223		
GCV	44.3995		
Deviance explained	26.1%		

Table B.13. Best-fitting generalized additive model for predicting adult Northern Abalone ($\geq$ 70 mm shell length) density using environmental variables in the Southern BC dataset in 1978-2018.

Term	**df/edf**	**F**	**p-value**
Year	7	3.79	0.00073
Substrate	1.883	3.179	0.03511
Salinity	1	11.24	0.00097
residual	177.117		
GCV	24.2262		
Deviance explained	22.6%		

Table B.14. Best-fitting generalized additive model for predicting adult Northern Abalone ($\geq$ 70 mm shell length) density using environmental variables in the Southern BC dataset in 2006-2018.

Term	**df/edf**	**F**	**p-value**
Year	4	2.18	0.07519
Pycnopodia	1	11.046	0.00115
residual	127		
GCV	22.838		
Deviance explained	15.6%		

Table B.15. Best-fitting generalized additive model for predicting large Northern Abalone ($\geq$ 100 mm shell length) density using environmental variables in the Southern BC dataset in 1978-2018.

Term	**df/edf**	**F**	**p-value**
Otter.PA	1	59.72	<0.0001
Year	7	3429.82	<0.0001
Tides	1.995	2473.407	<0.0001
VRM	1.961	562.461	<0.0001
Bathy	1.043	111.819	<0.0001
TPI	1.01	26.975	<0.0001
TRI	1.984	214.52	<0.0001
residual	171.008		
GCV	-28.8012		
Deviance explained	85%		

Table B.16. Best-fitting generalized additive model for predicting large Northern Abalone ($\geq$ 100 mm shell length) density using environmental variables in the Southern BC dataset in 2006-2018.

Term	**df/edf**	**F**	**p-value**
Year	3	0	1
Tides	1.851	9.567	4e-04
residual	92.149		
GCV	-51.1764		
Deviance explained	65.6%		

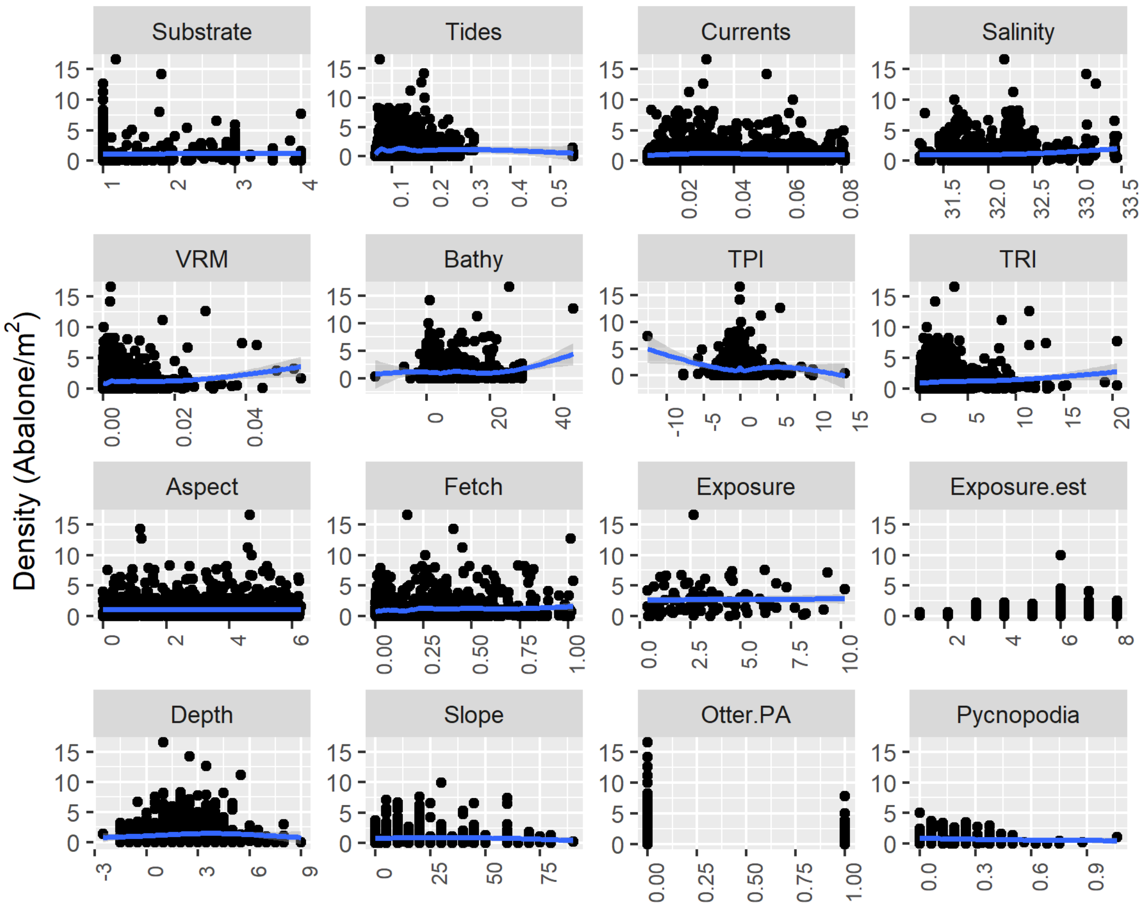


Figure B.1. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of total Northern Abalone (shell length $\geq$ 20 mm) using the Northern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

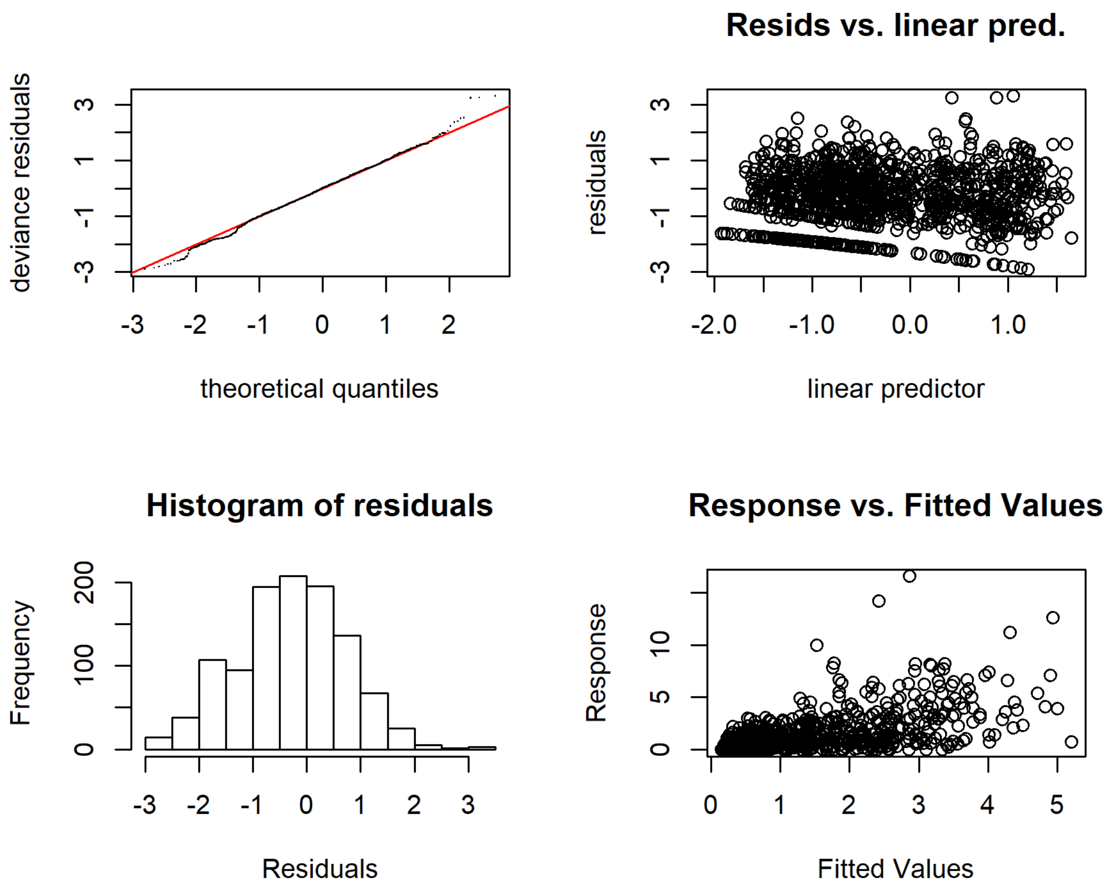


Figure B.2. Plots of residuals of the best-fitting generalized additive model fit to total (shell length $\geq$ 20 mm) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

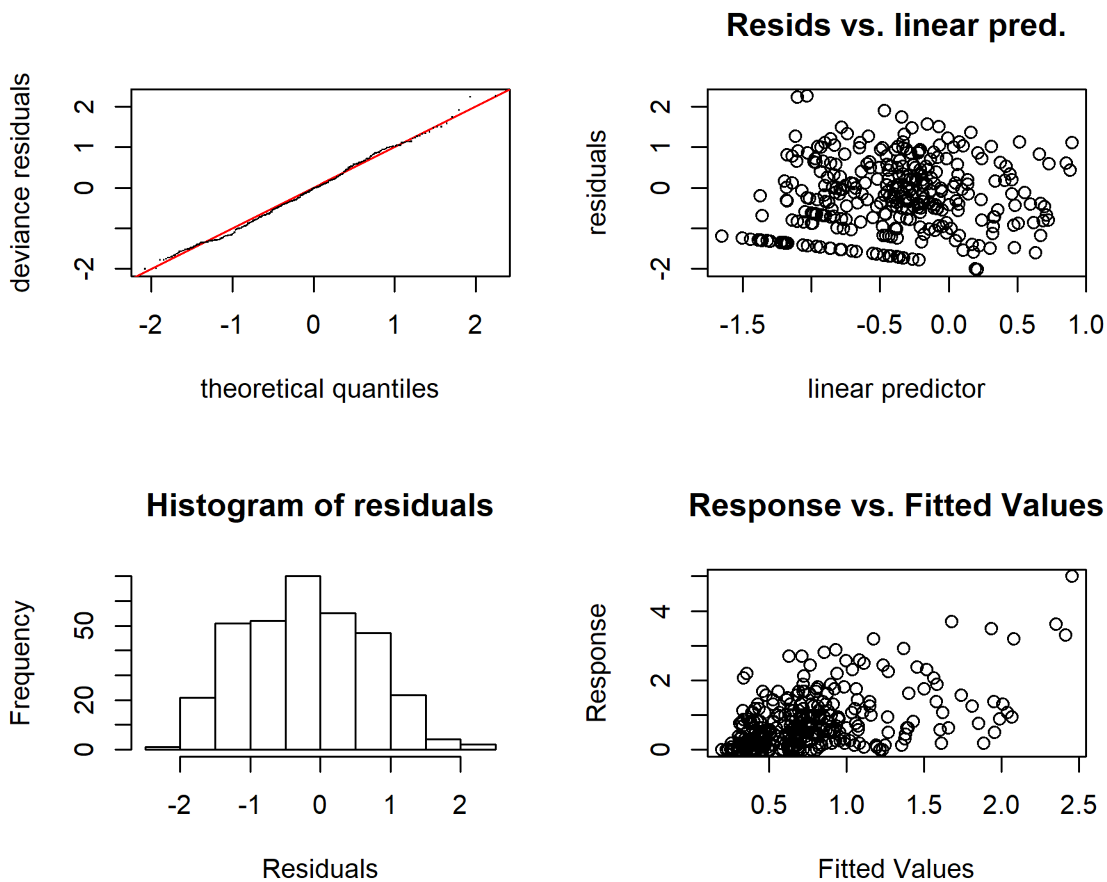


Figure B.3. Plots of residuals of the best-fitting generalized additive model fit to total (shell length $\geq$ 20 mm) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

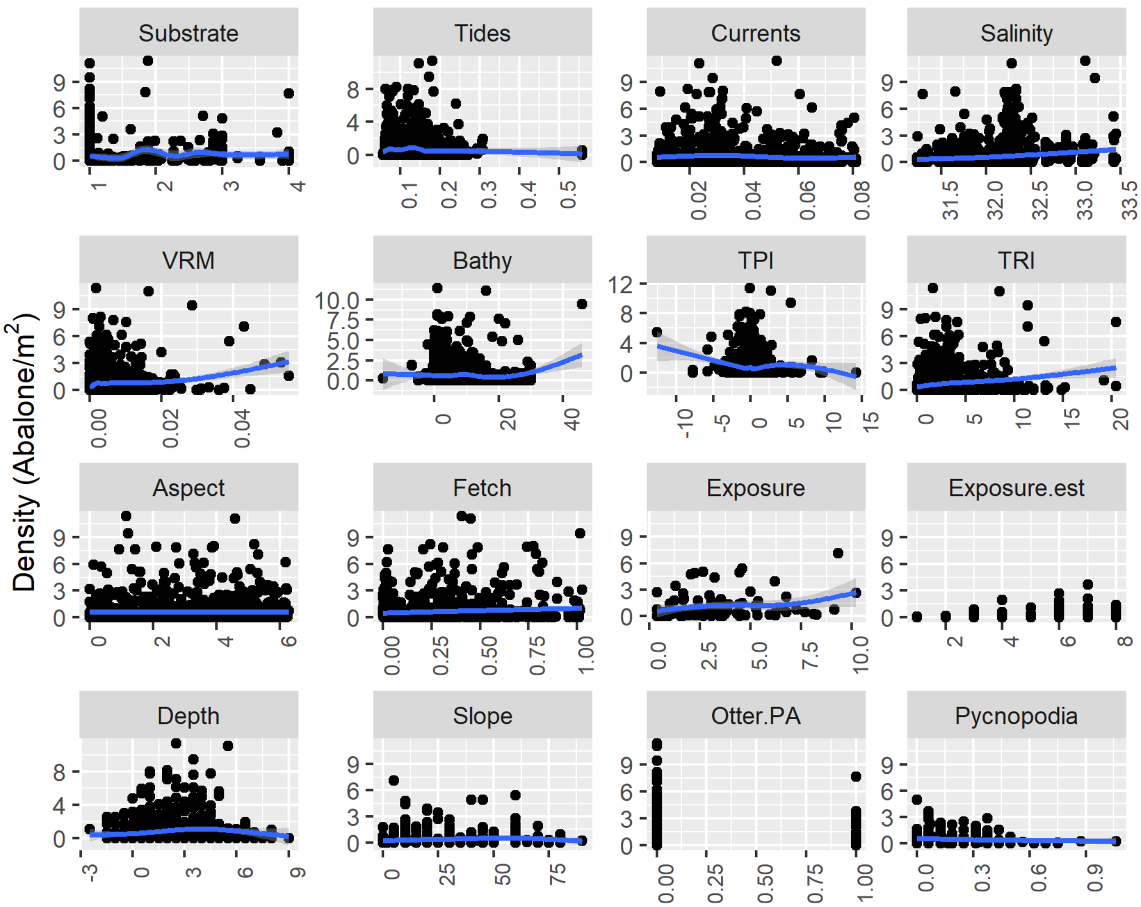


Figure B.4. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) using the Northern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

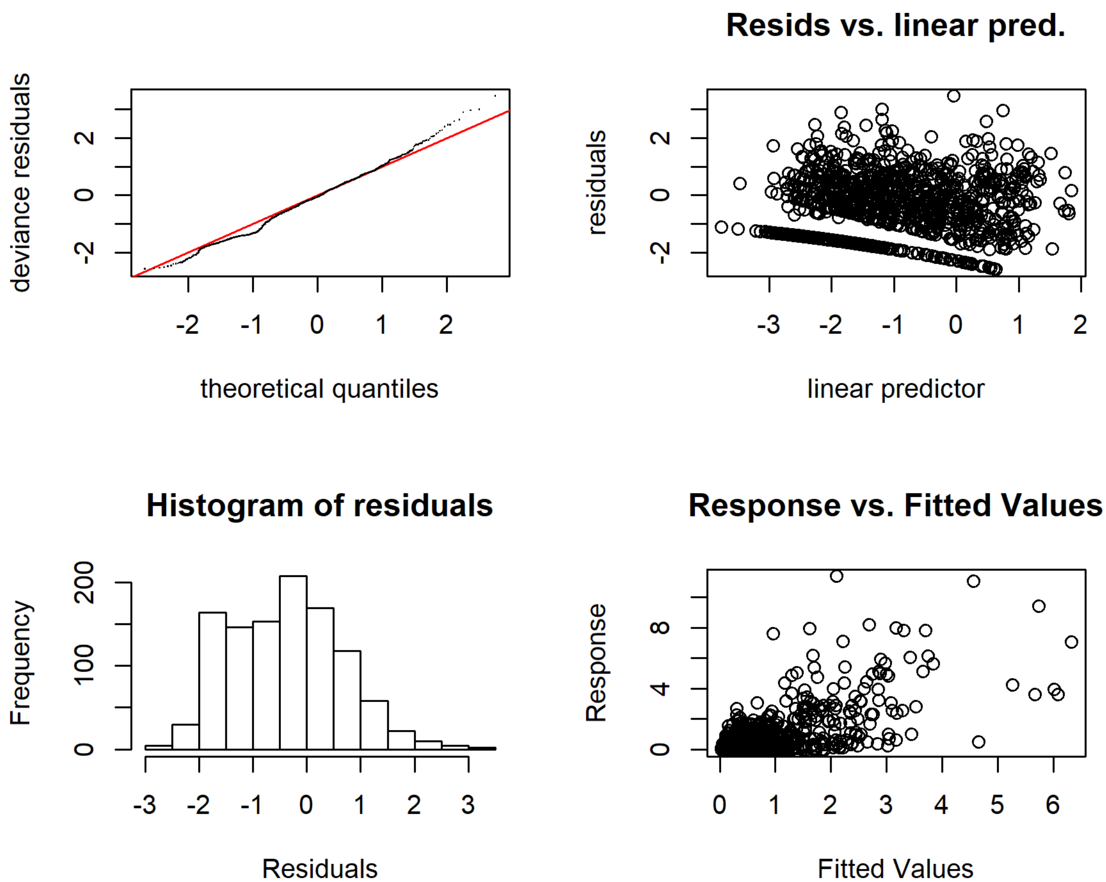


Figure B.5. Plots of residuals of the best-fitting generalized additive model fit to juvenile ($\geq$ 20 mm to $<$70 mm shell length) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

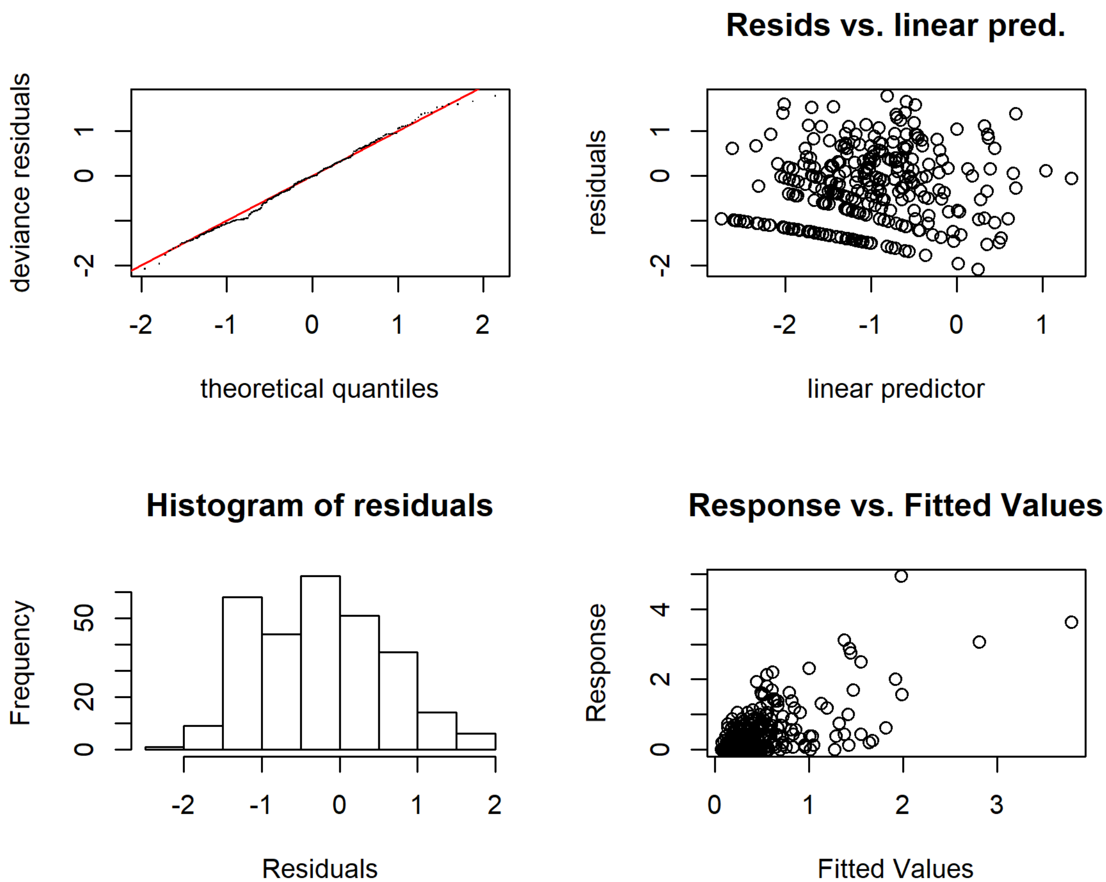


Figure B.6. Plots of residuals of the best-fitting generalized additive model fit to juvenile ($\geq$ 20 mm to $<$70 mm shell length) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

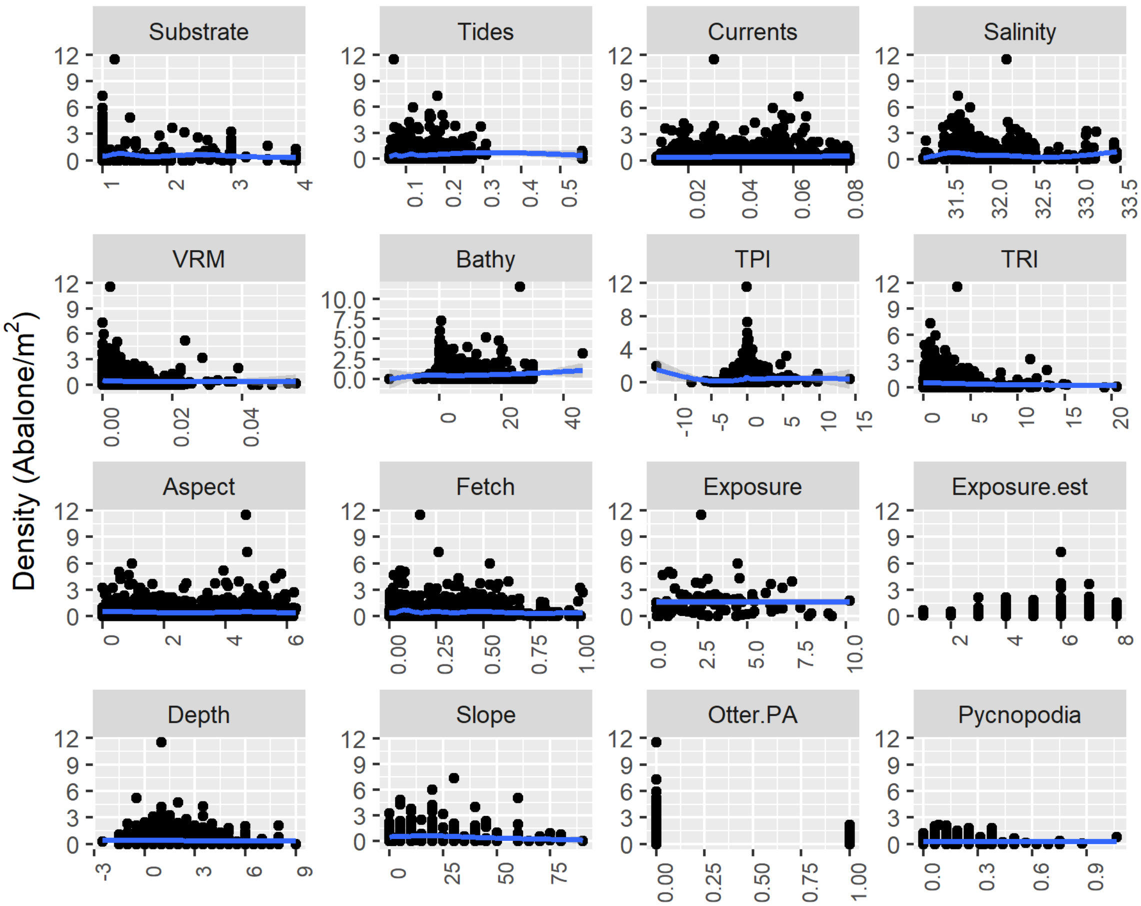


Figure B.7. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of adult Northern Abalone (shell length $\geq$ 70 mm) using the Northern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

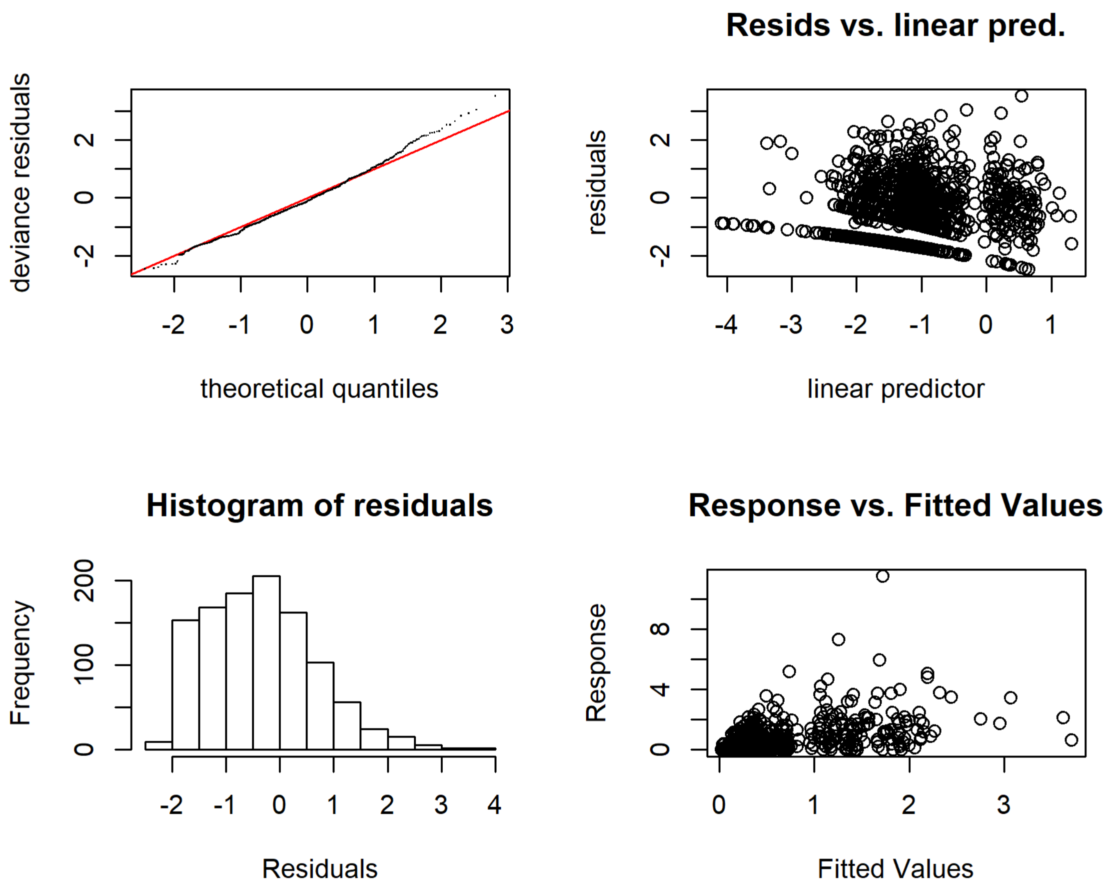


Figure B.8. Plots of residuals of the best-fitting generalized additive model fit to adult (shell length $\geq$ 70 mm) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

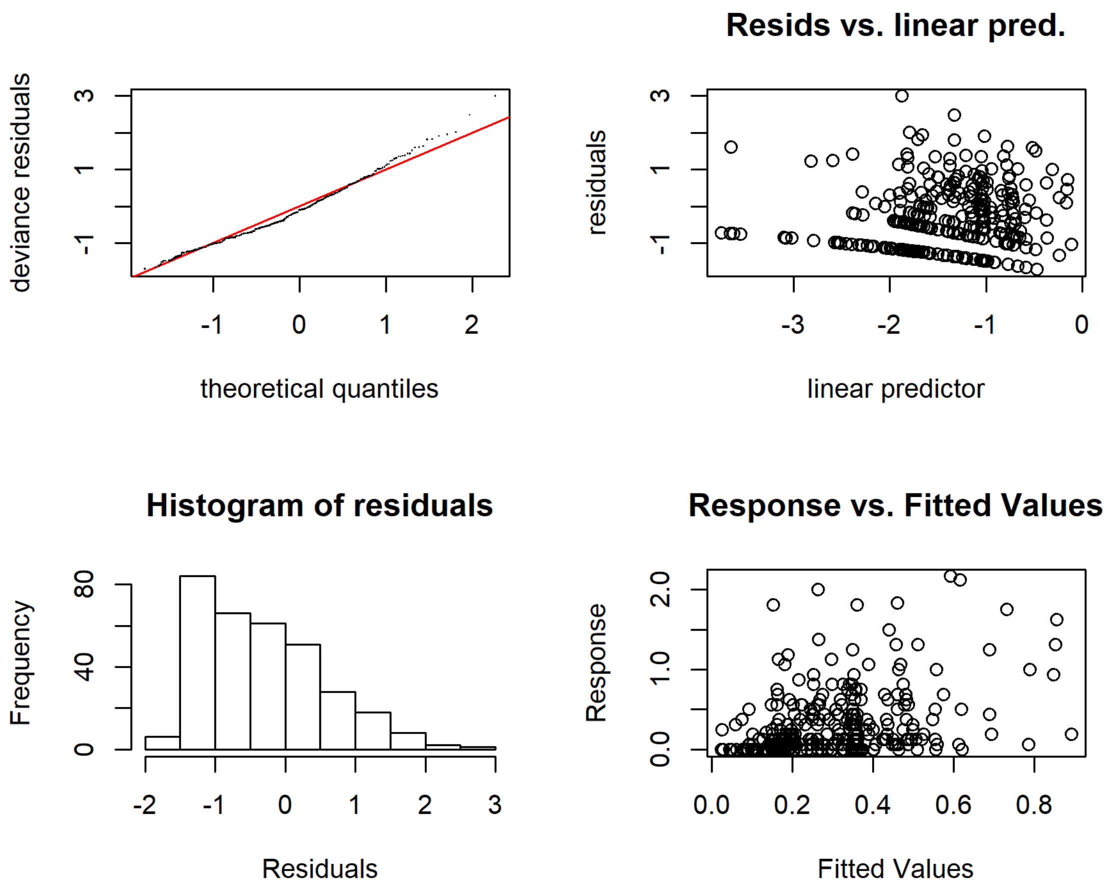


Figure B.9. Plots of residuals of the best-fitting generalized additive model fit to adult (shell length $\geq$ 70 mm) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

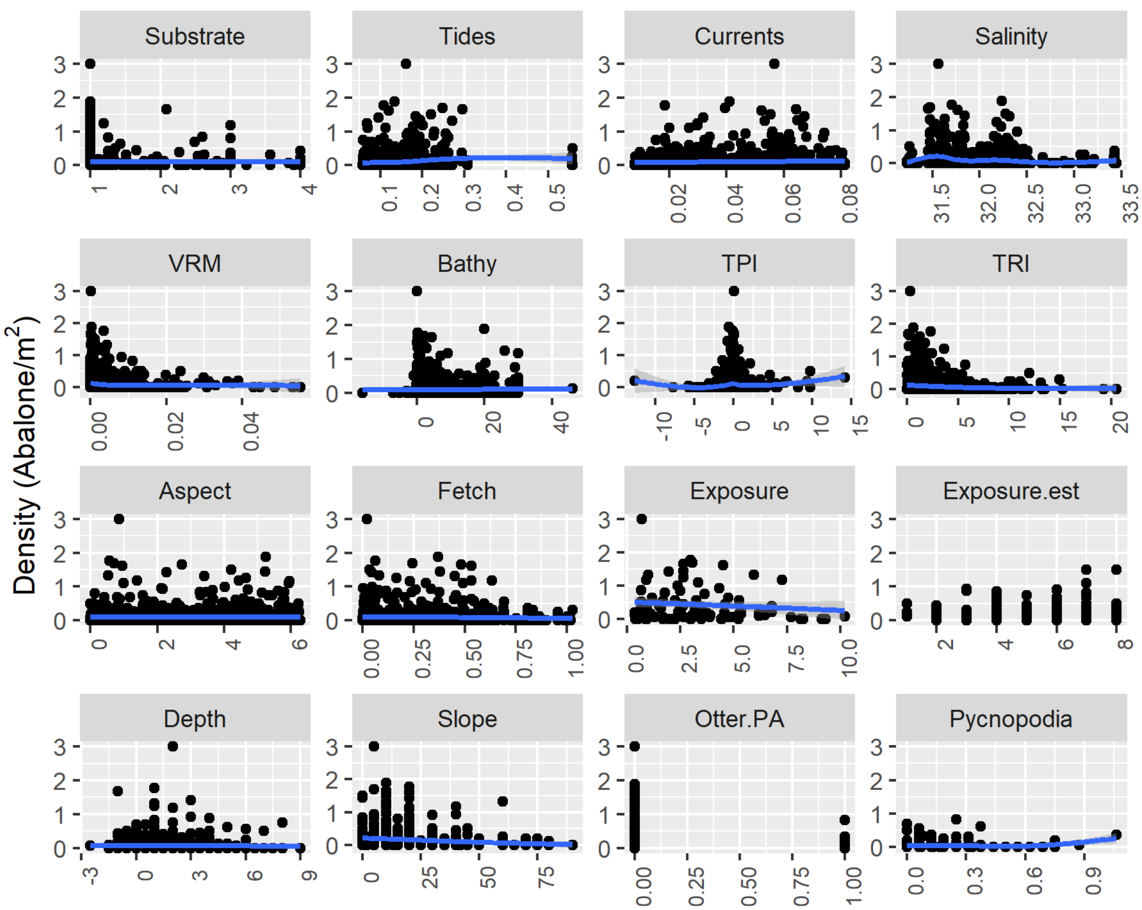


Figure B.10. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of large Northern Abalone (shell length $\geq$ 100 mm) using the Northern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

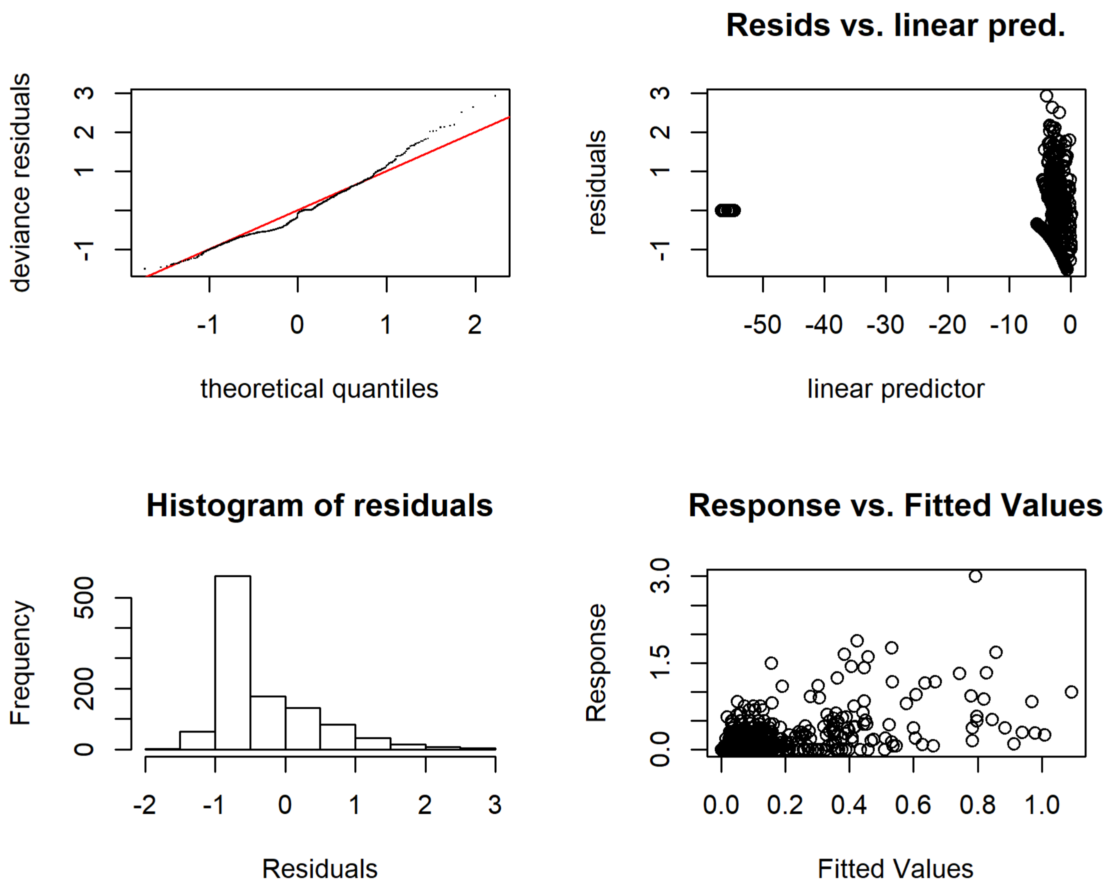


Figure B.11. Plots of residuals of the best-fitting generalized additive model fit to large (shell length $\geq$ 100 mm) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

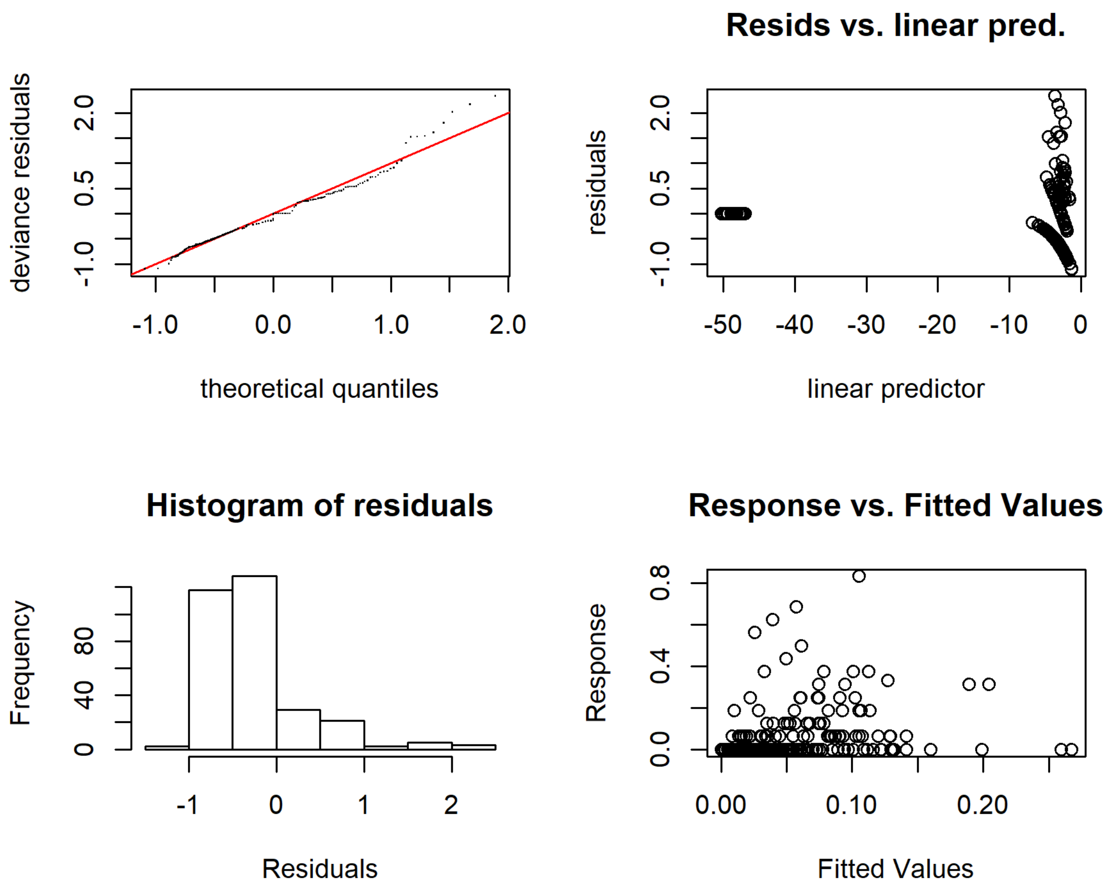


Figure B.12. Plots of residuals of the best-fitting generalized additive model fit to large (shell length ≥ 100 mm) Northern Abalone density data using environmental variables. The data used are from the Northern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

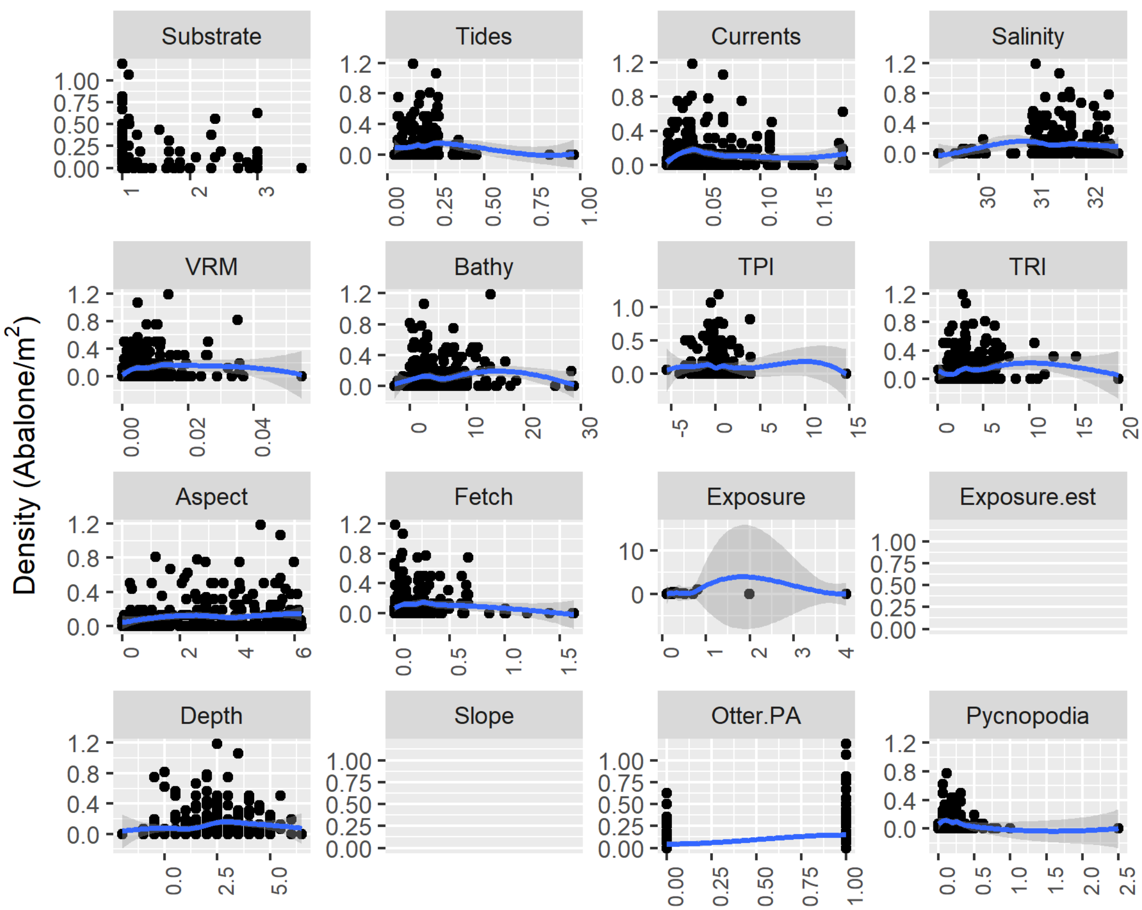


Figure B.13. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of total Northern Abalone (shell length $\geq$ 20 mm) using the Southern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

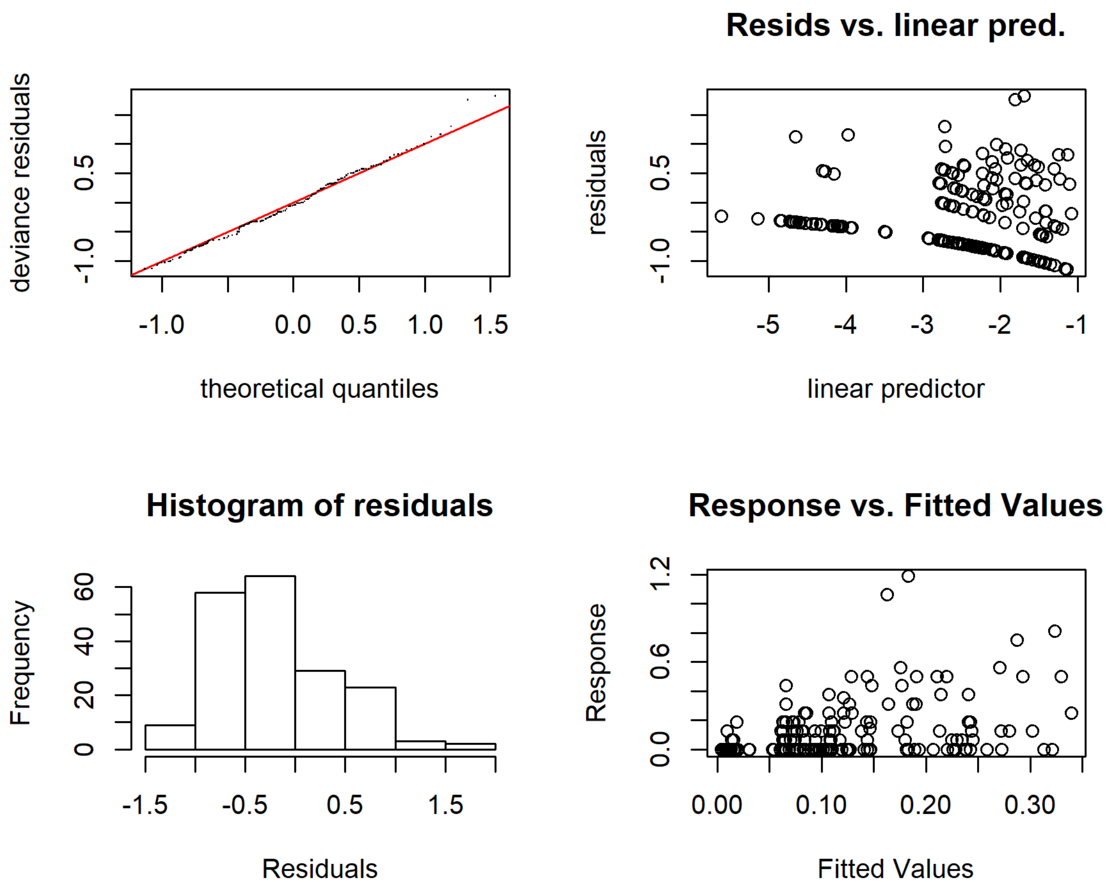


Figure B.14. Plots of residuals of the best-fitting generalized additive model fit to total (shell length $\geq$ 20 mm) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

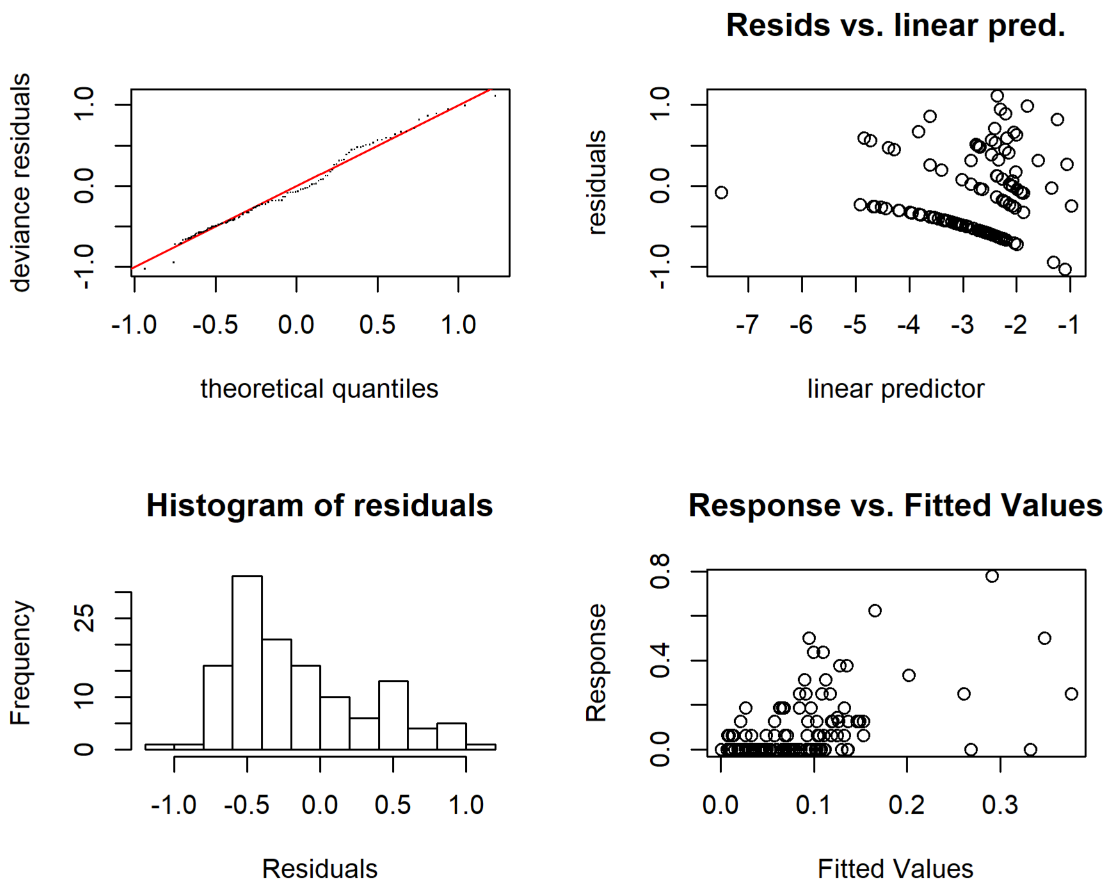


Figure B.15. Plots of residuals of the best-fitting generalized additive model fit to total (shell length $\geq$ 20 mm) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

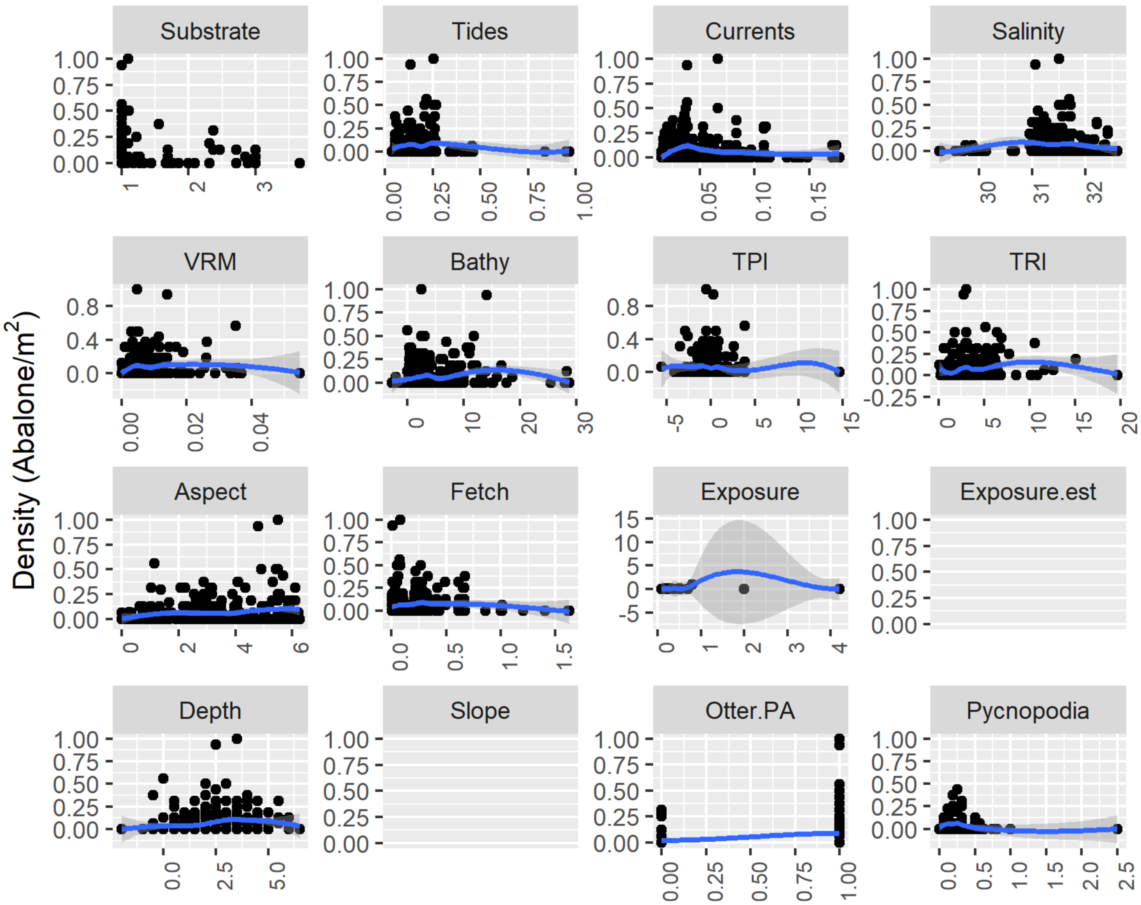


Figure B.16. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) using the Southern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

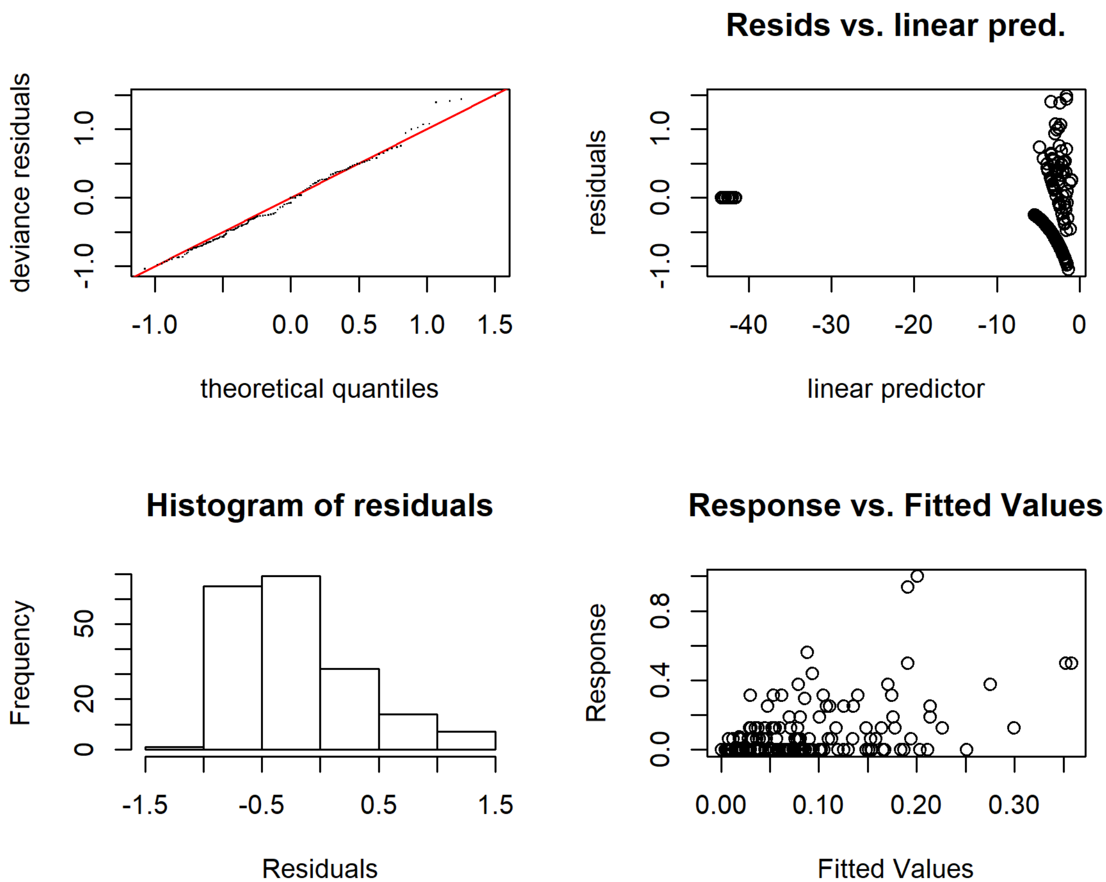


Figure B.17. Plots of residuals of the best-fitting generalized additive model fit to juvenile ($\geq$ 20 mm to $<$70 mm shell length) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

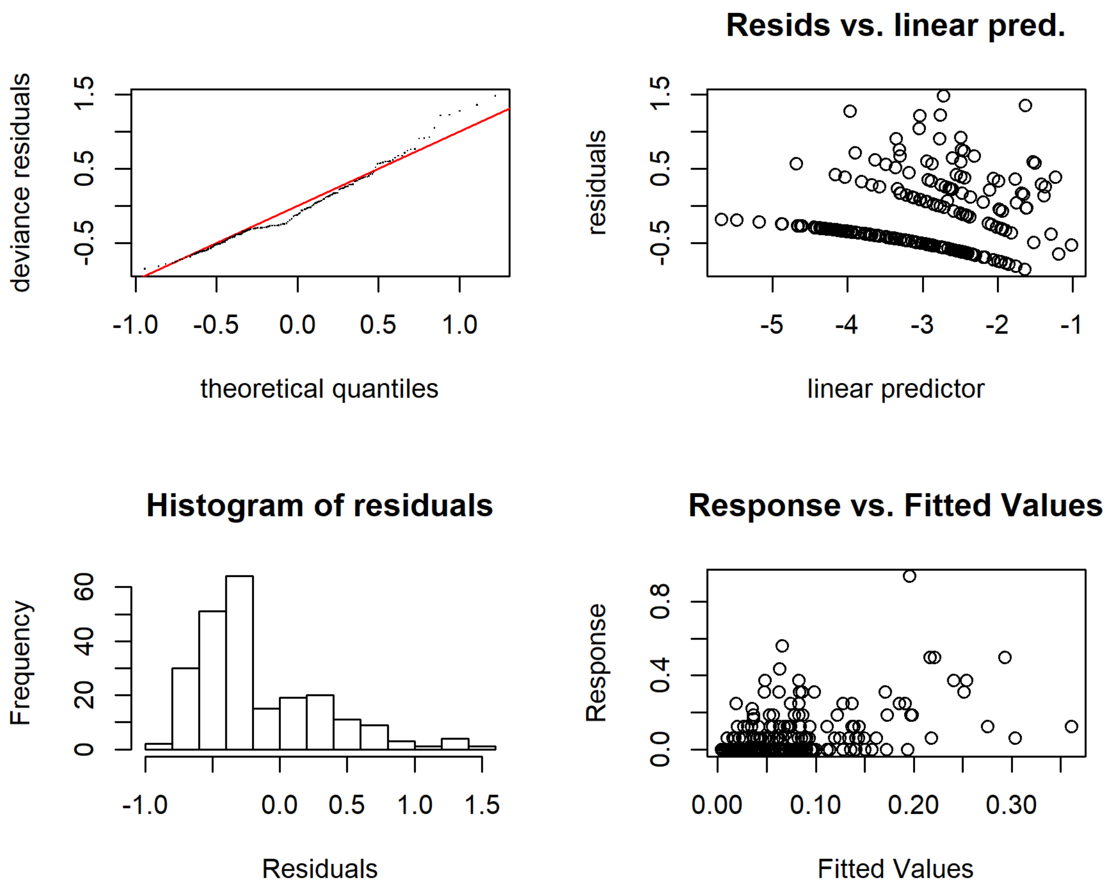


Figure B.18. Plots of residuals of the best-fitting generalized additive model fit to juvenile ($\geq$ 20 mm to <70 mm shell length) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

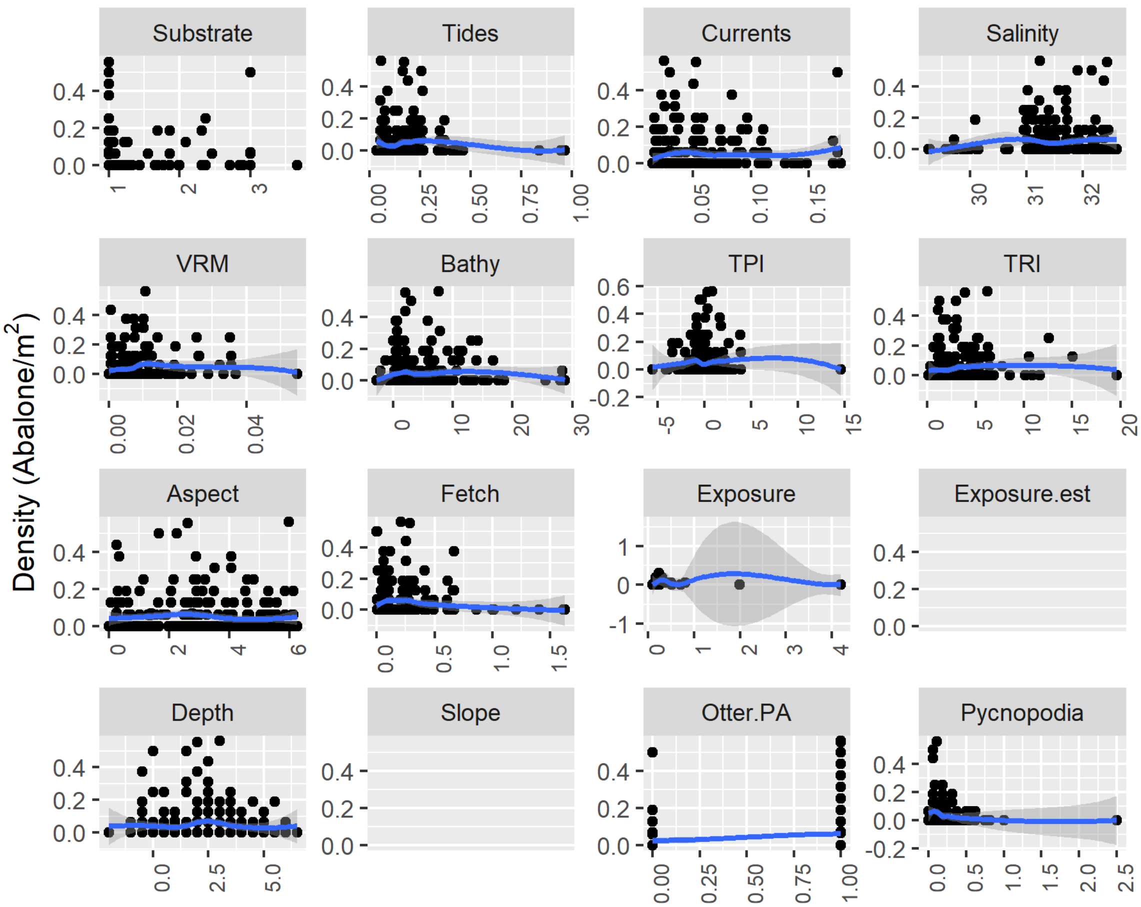


Figure B.19. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of adult Northern Abalone (shell length $\geq$ 70 mm) using the Southern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

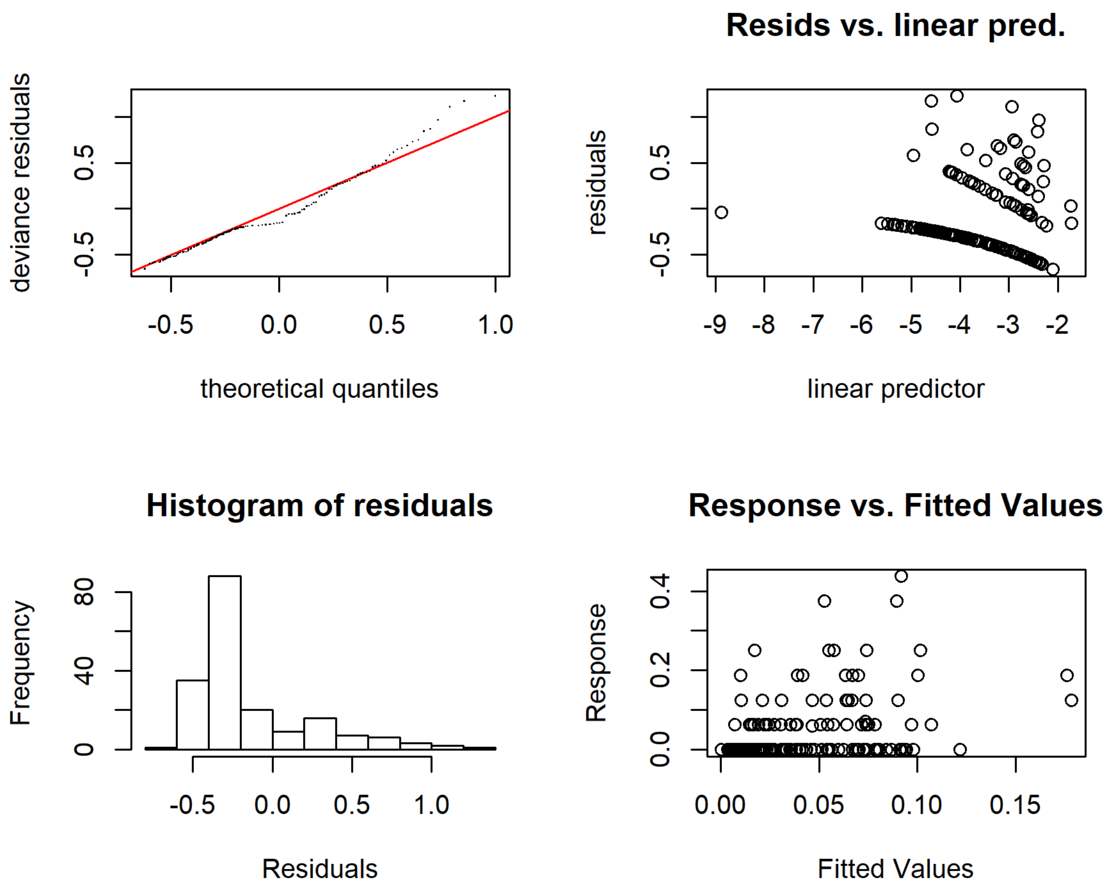


Figure B.20. Plots of residuals of the best-fitting generalized additive model fit to adult (shell length $\geq$ 70 mm) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

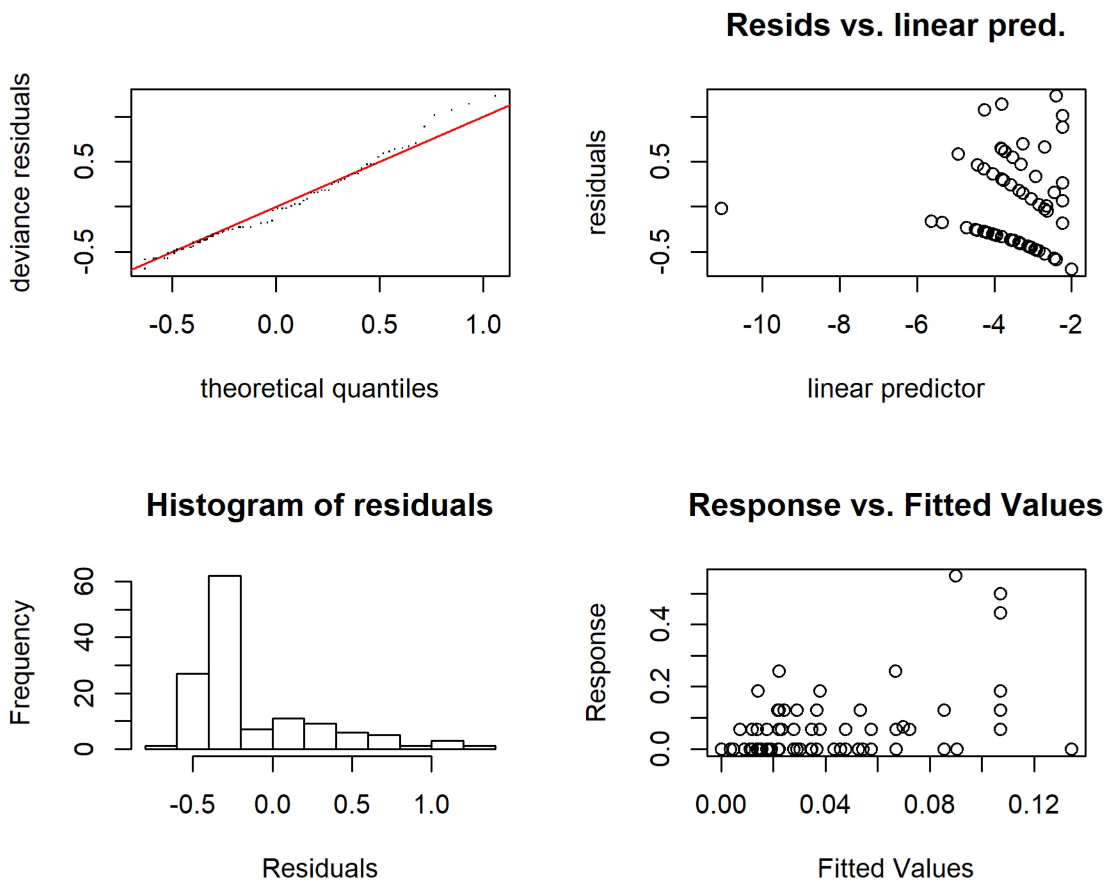


Figure B.21. Plots of residuals of the best-fitting generalized additive model fit to adult (shell length $\geq$ 70 mm) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

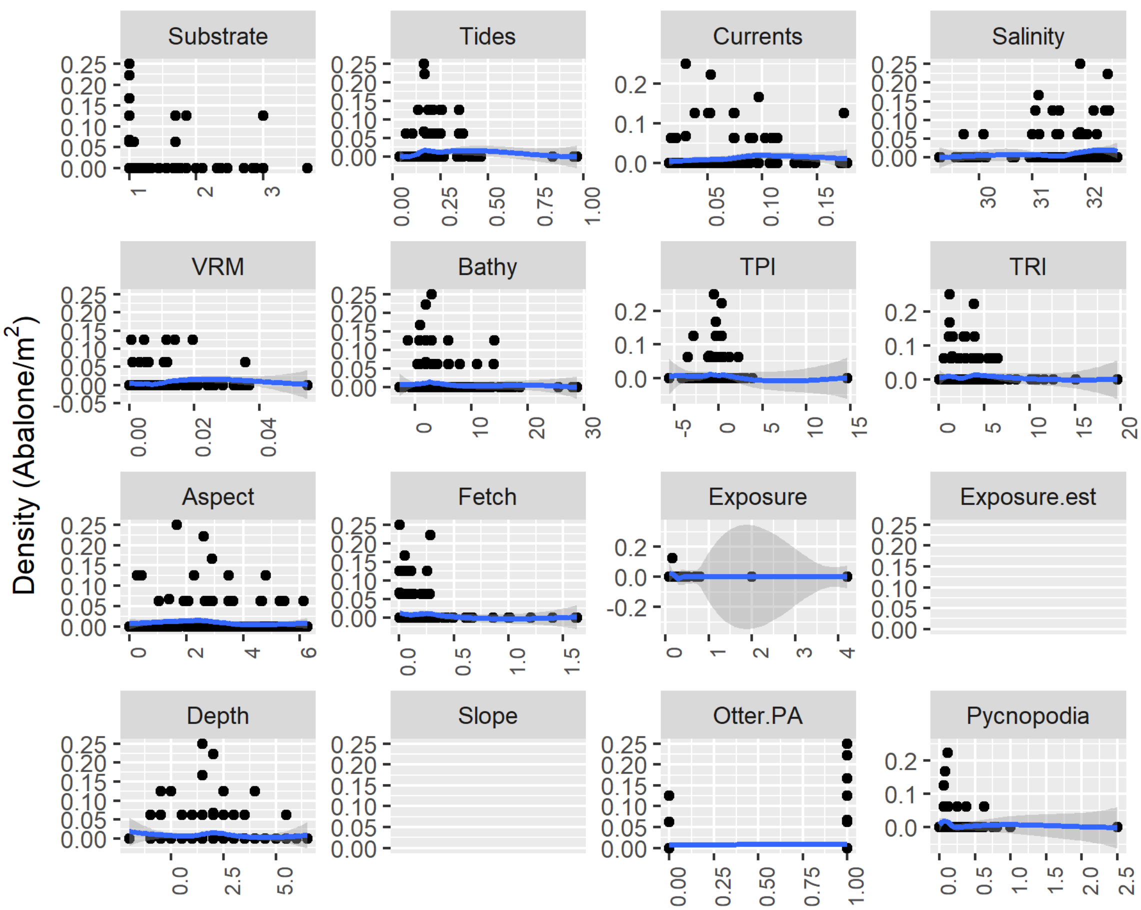


Figure B.22. Scatter plots of potential environmental variables for standardizing Northern Abalone abundance indices and the observed density of large Northern Abalone (shell length $\geq$ 100 mm) using the Southern BC dataset. The line shows the smoothed trend in Northern Abalone density over the range of each explanatory variable.

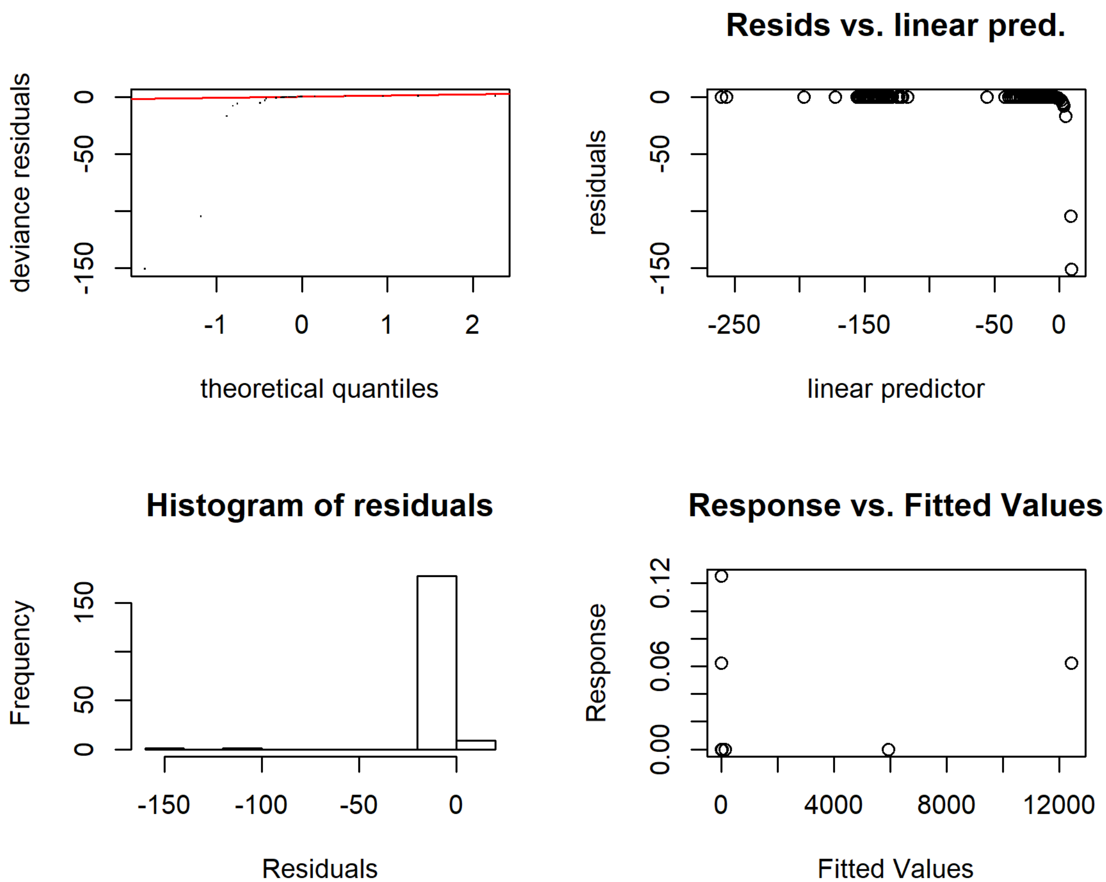


Figure B.23. Plots of residuals of the best-fitting generalized additive model fit to large (shell length $\geq$ 100 mm) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (1978-2018) and the model utilizes Tweedie-distributed errors.

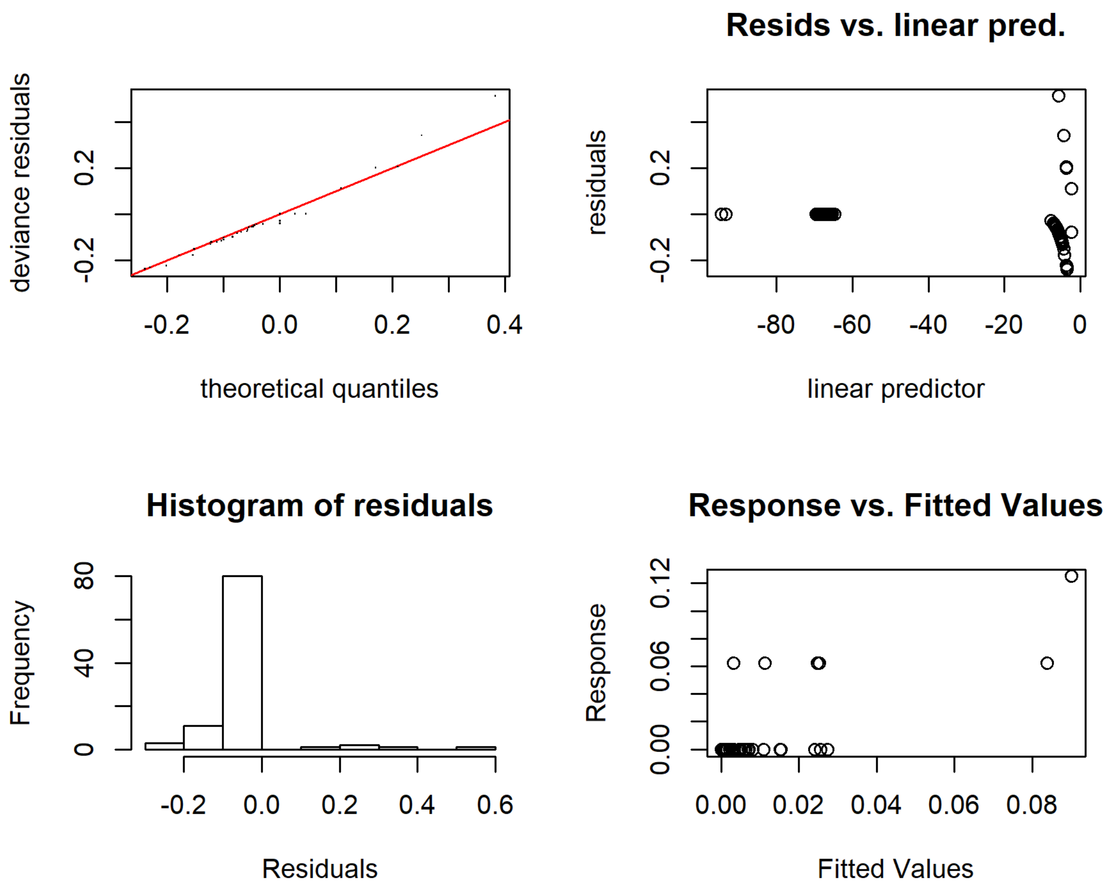


Figure B.24. Plots of residuals of the best-fitting generalized additive model fit to large (shell length $\geq$ 100 mm) Northern Abalone density data using environmental variables. The data used are from the Southern BC dataset (2006-2018) and the model utilizes Tweedie-distributed errors.

APPENDIX C EXAMPLE OF THE INTERACTION BETWEEN ENVIRONMENTAL VARIABLES AND YEAR

In some years, changes in the number of index sites surveyed (i.e. adding and subtracting index sites) created changes in the environmental variables, making it difficult to parse the relative effects of changes in abundance caused by recruitment or mortality, and changes in abundance caused by addition or subtraction of new sites. For example, Lessard and Campbell (2007), found that the density of Northern Abalone was correlated with their index of exposure. The Lessard and Campbell (2007) data on exposure were calculated over relatively few years (1978-1980) but are present in the DFO Northern Abalone database. For the CC region 1978-1980, the average exposure at index sites increased each year (Figure C.1). This corresponded to an increase in the density of juvenile Northern Abalone ($\geq$ 20 mm to $<$ 70 mm shell length). Thus, exposure is insignificant and the factor (year) is the only significant effect, since the effect of the two variables is not separable (Table C.1). In general, a categorical variable tends to account for more variance than a continuous variable, simply because of the effect of binning the data. This illustrates the confounding effects of year and environmental variables where adding, removing, and changing the locations of the sites can impact the annual abundance index.

In future work examining relationships between Northern Abalone and their environment, it might be interesting to remove the effect of interannual variability by calculating standardized anomalies of density within a year at each site, so that each year had a mean of 0 and standard deviation of 1. This would allow a more directed comparison of the differences in site-site variation in relation to environmental variables. This analysis could provide insight into how to best standardize or stratify future changes to Northern Abalone surveys of the index sites.

Table C.1. Best-fitting generalized additive model for predicting juvenile Northern Abalone ($\geq$ 20 mm to $<$70 mm shell length) density using a model with only year and exposure effects. Only data from the Central Coast from 1978-1980 were included in this analysis.

Term	df/edf	F	p-value
Year	2	4.24	0.02178
Exposure	1	0.015	0.90173
residual	38		
GCV	1.0352		
Deviance explained	22.1%		

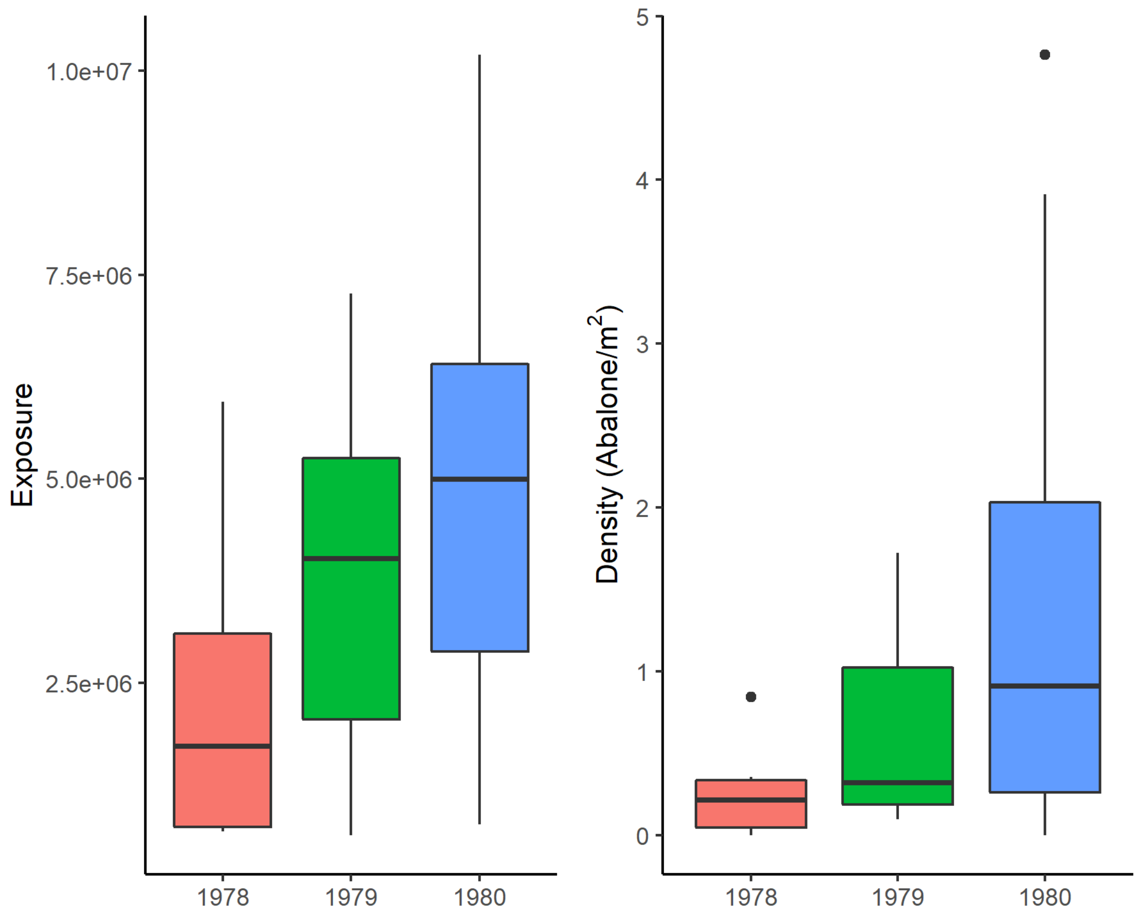


Figure C.1. Comparison of exposure calculations by year (1978-1980) and density of juvenile ($\geq$ 20 mm to $<$70 mm shell length) Northern Abalone by year (1978-1980) at Central Coast Northern Abalone index sites.