

**Pinto Abalone (*Haliotis kamtschatkana* Jonas 1845)
Surveys in Southern Southeast Alaska, 2016**

by

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and

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Alaska Department of Fish and Game

Divisions of Sport Fish and Commercial Fisheries



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Weights and measures (metric)		General		Mathematics, statistics	
centimeter	cm	Alaska Administrative Code	AAC	all standard mathematical signs, symbols and abbreviations	
deciliter	dL	all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.	alternate hypothesis	H _A
gram	g	all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.	base of natural logarithm	e
hectare	ha			catch per unit effort	CPUE
kilogram	kg	at	@	coefficient of variation	CV
kilometer	km			common test statistics	(F, t, χ^2 , etc.)
liter	L	compass directions:		confidence interval	CI
meter	m	east	E	correlation coefficient (multiple)	R
milliliter	mL	north	N	correlation coefficient (simple)	r
millimeter	mm	south	S	covariance	cov
Weights and measures (English)		west	W	degree (angular)	°
		copyright	©	degrees of freedom	df
cubic feet per second	ft³/s	corporate suffixes:		expected value	E
foot	ft	Company	Co.	greater than	>
gallon	gal	Corporation	Corp.	greater than or equal to	≥
inch	in	Incorporated	Inc.	harvest per unit effort	HPUE
mile	mi	Limited	Ltd.	less than	<
nautical mile	nmi	District of Columbia	D.C.	less than or equal to	≤
ounce	oz	et alii (and others)	et al.	logarithm (natural)	ln
pound	lb	et cetera (and so forth)	etc.	logarithm (base 10)	log
quart	qt	exempli gratia		logarithm (specify base)	log ₂ , etc.
yard	yd	(for example)	e.g.	minute (angular)	'
Time and temperature		Federal Information Code	FIC	not significant	NS
		id est (that is)	i.e.	null hypothesis	H ₀
day	d	latitude or longitude	lat or long	percent	%
degrees Celsius	°C	monetary symbols		probability	P
degrees Fahrenheit	°F	(U.S.)	\$, ¢	probability of a type I error (rejection of the null hypothesis when true)	α
degrees kelvin	K	months (tables and figures): first three letters	Jan,...,Dec	probability of a type II error (acceptance of the null hypothesis when false)	β
hour	h	registered trademark	®	second (angular)	"
minute	min	trademark	™	standard deviation	SD
second	s	United States (adjective)	U.S.	standard error	SE
Physics and chemistry		United States of America (noun)	USA	variance	
		U.S.C.	United States Code	population sample	Var var
all atomic symbols		U.S. state	use two-letter abbreviations (e.g., AK, WA)		
alternating current	AC				
ampere	A				
calorie	cal				
direct current	DC				
hertz	Hz				
horsepower	hp				
hydrogen ion activity (negative log of)	pH				
parts per million	ppm				
parts per thousand	ppt, ‰				
volts	V				
watts	W				

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ABSTRACT

Pinto abalone (*Haliotis kamtschatkana*) is listed as a species of concern under the U.S. Endangered Species Act (ESA), and is listed as endangered by Canada and the International Union for Conservation of Nature. The status of pinto abalone in Southeast Alaska, the northernmost portion of its range, is largely unknown. Based on recommendations from a recent ESA status review, we conducted this study to fill basic knowledge gaps on population status in two areas of former abalone abundance in Southeast Alaska, one with and one without sea otters, and to establish long-term monitoring index sites for tracking population status over time. During four days in July 2016, we collected data at 15 sites (1 historical, 14 new) along Gravina Island and 10 sites (all historical) in Meares Pass. Timed swims and transects were used to obtain relative and absolute density data, as well as length measurements. Length frequency distributions were statistically different between methods (Gravina only) and between areas, indicating sampling bias and possible effects of sea otter predation, respectively. Average abalone absolute densities ($\pm$ SE) at Gravina Island and Meares Pass were $0.29/\text{m}^2$ (0.08) and $0.17/\text{m}^2$ (0.03), respectively. Area- and site-specific densities were near or below the threshold for population collapse and recruitment failure reported in the literature ($0.2/\text{m}^2$). Timed swim data from Meares Pass were compared to historical surveys from 1980–1981, and corresponded to a steep decline shown by commercial fishery catch data. There was no relationship between site-specific relative and absolute density, so the interpretation of relative density was unclear. The length frequency distribution was much smaller in 2016 than in the 1980s, but sampling bias could not be ruled out. Overall, there was cause for concern, but length frequency data showing recent and regular recruitment to the populations in both study areas was encouraging.

Key words: pinto abalone, *Haliotis kamtschatkana*, Southeast Alaska, density, size frequency, field survey

INTRODUCTION

The pinto abalone (*Haliotis kamtschatkana* Jonas 1845) is the northernmost abalone species on the west coast of North America, and the only abalone species found in Alaska. Historically in Southeast Alaska, abalone have been found primarily in or near outer coastal environments that experience ocean swells, including Dixon Entrance and west sides of Baranof Island, Prince of Wales Island, and Dall Island (Figure 1). Within these areas, abalone occupy rocky habitat within the lower intertidal and shallow subtidal zones.

Pinto abalone were intensively harvested in Alaska during a commercial fishery that operated from 1970 to 1996. The peak catch occurred between 1978 and 1981 and was followed by an 89% decline in total catch, which prompted the indefinite closure of the commercial fishery by the Alaska Department of Fish and Game (ADF&G) after the 1995–1996 season (Woodby et al. 2000; McDougall et al. 2006). Legal harvest of pinto abalone in personal use and subsistence fisheries has continued to present. These fisheries are currently limited by a prohibition of using compressed air breathing systems (e.g., SCUBA, hookah), a minimum size limit of 89 mm, and a daily bag limit of 5 per day. Until regulations changed in 2012, the bag limit for abalone was 50 per person per day (except in the Sitka area, where it was 20 per person per day), with no annual limit. No reporting is required for these fisheries, and harvested quantities are assumed by ADF&G to be non-significant. The extent of illegal harvest in Southeast Alaska is unknown, but commercial-scale poaching assumed to be minimal due to lack of easy access to black markets. However, the coastline of Southeast Alaska is vast and largely uninhabited, enforcement resources are limited, and the southern part of the region is in close proximity to British Columbia, where poaching has been a problem (Zhang et al. 2007).

The most important factor thought by many to be hindering abalone recovery in Southeast Alaska is intensive predation by re-introduced sea otters (*Enhydra lutris*) (e.g., Woodby et al. 2000). Sea otters have made a spectacular comeback in Southeast Alaska (Esslinger and Bodkin 2009), growing from 402 transplanted individuals in the late 1960s (Pitcher 1989) to 25,712 in

2014 (U.S. Fish and Wildlife Service 2014). Sea otter recolonization can be characterized by an exponential increase in abundance coincident with geographic expansion from transplant locations to other outer coastal areas, as well as penetration into food-rich wave-protected waters, most notably Glacier Bay (Esslinger and Bodkin 2009). Pinto abalone do not have a depth refugia from sea otters (Bodkin et al. 2004), but they can find refuge in interstitial spaces in rocky habitat. However, sea otter predation does not directly explain why pinto abalone abundance apparently has apparently remained depressed in the eastern and northern portion of the Dixon Entrance, where sea otters have not recolonized to date. There has been anecdotal evidence for temporary forays by male scouts in this area, but not resident individuals (S. Walker, ADF&G, personal communication). ADF&G's personal use and subsistence fisheries cannot be ruled out as a possible explanation for the apparent lack of recovery in this area.

If human harvest and sea otter predation have not been important factors in inhibiting recovery, then plausible hypotheses for lack of pinto abalone recovery in Southeast Alaska may include demographic stochasticity at low population abundance and densities (Stephens et al. 1999), recruitment failure (e.g., Rothaus et al. 2008), biological microhabitat conversion (Miner et al. 2006), individual- and/or population-level responses to natural environmental fluctuations (e.g., Pacific decadal oscillation) and climate change-related influences (e.g., ocean warming and acidification) (Rogers-Bennett 2007; Ben-Horin 2013).

The National Marine Fisheries Service (NMFS) recently conducted a status review of the pinto abalone under the Endangered Species Act (ESA) to determine if the status should be elevated to threatened or endangered (Busch et al. 2014). Ultimately, they decided to retain the lesser Species of Concern designation, primarily because the information available did not suggest danger of extinction in the near or foreseeable future. A major impediment to the investigation by the NMFS Status Review Team of pinto abalone stock status in Alaska was a lack of baseline and current information (Busch et al. 2014). This problem was also noted by the International Union for the Conservation of Nature in their assessment of pinto abalone (McDougall et al. 2006), which listed collection of fishery-independent datasets from index monitoring sites in Alaska as one of its top three recommended research priorities. Long-term monitoring programs in Washington State (Rothaus et al. 2008) and British Columbia (reviewed in Busch et al. 2014), have tracked the absolute abalone density at index sites for over two decades, which has provided critical information on the magnitude of population declines and, in the case of the latter, promising new signs that poaching enforcement is working. In contrast, abalone research in Alaska has been lacking, even prior to the commercial fishery closure in 1996, when the incentive to fill key information gaps in abalone biology and population dynamics for purposes of a sustainable fishery was more urgent. There have been some Alaska-specific published studies on age and growth (Paul and Paul 1981, 2000; Woodby et al. 2000) and unpublished work on population size structure (Larson and Blankenbeckler 1980; ADF&G unpublished data), but no stock assessments or surveys of absolute density were attempted until 2015 (Bell et al. *in prep*). There were relative density and length frequency surveys that targeted abalone over a large geographic area in Southeast Alaska in 1979–1981 (Larson and Blankenbeckler 1980; ADF&G unpublished data), but subsequent surveys were limited. The ADF&G has conducted spatially and temporally intensive stock assessments for sea cucumbers and sea urchins since the mid-1990s, and some abalone observations were opportunistically recorded during those surveys (ADF&G unpublished data). There is an apparent trend of declining abundance in those datasets

that mirrors declines in other regions, but the absence of a formal survey protocol and the opportunistic, inconsistent nature of the data collection limited its utility.

This study was initiated by the NMFS in response to identification of key knowledge gaps in the ESA status review. Little is known about the current status of the population or how it has changed over time, and therefore whether the current management regime is sufficiently conservative. The purpose of this study was to obtain a “snapshot” of local abalone populations at multiple sites within each of two small study areas in Southeast Alaska where abalone were known to be formerly abundant, and use these sites as the basis for future long-term monitoring to track population status over time. Sites with historical abalone data were prioritized over establishing new sites. Whether abalone populations can sustain ongoing subsistence and personal use fisheries in Southeast Alaska, and whether this answer may differ as a function of sea otter occupation status, are the primary research questions that ADF&G seeks to address in this study. We will use our recent pinto abalone research and monitoring work in Sitka Sound (Alaska Sea Grant No. R/100-03 “Coastal Resilience in Sitka Sound: Monitoring Pinto Abalone and Kelp Forests in a Changing Climate”) as the foundation for this study.

OBJECTIVES

The primary objective of this study was to establish at least 10 index sites in each of two study areas, within the time constraint of two consecutive days per study area. The secondary objective was to collect baseline data for the most informative population metrics (e.g., density, size structure) possible using statistically robust, repeatable methods. For this study, we defined the term *baseline* as an initial dataset to provide a reference point for future comparisons; this definition should not be confused with the other common definition in which the benchmark is considered to be prior to significant human harvest.

STUDY DESIGN

This study was primarily descriptive in nature (i.e. to establish a baseline dataset), but also included several testable hypotheses to evaluate the status of the population and to inform future survey design. The specific questions investigated included (organized according to metric class):

Size structure

- What was the size structure (length frequency) of the abalone population within each study area?
- Did the size structure vary at the spatial scale of sites within a study area?
- Did the size structure differ by method (timed swim vs. transect)?
- Did the size structure differ between study areas?
- What was the proportion of estimated lengths in the length frequency dataset for each method?
- What was the proportion of abalone exhibiting cryptic behavior in the length frequency dataset? Cryptic behavior was defined as any behavior by an individual abalone that served to conceal itself physically and/or visually (e.g., residing deep in crevices, or under boulders or algal fronds).
- Was there a relationship between abalone length and depth?
 - For timed swims?

- For transects?
- Did the size structure differ between current and historical data at Meares Pass?
- Was the size structure indicative of a sustainable population?
 - Was there evidence for recent recruitment to the population?
 - What was the length at full selectivity (i.e., near 100% detectability in the context of visual surveys)?
 - Was there evidence of large numbers of small abalone that would be indicative of recent recruitment events?
 - Was the maximum size observed the same as or different from the maximum size reported in the literature?
 - Did the size structure meet the California Department of Fish and Wildlife's criterion 1 ("broad size distribution of the former abalone range") described in their Abalone Recovery and Management Plan (CDFW 2005)?
 - Was the site occupation rate $\geq 40\%$ for large adult (≥ 100 mm) abalone, as specified in Canada's recovery strategy (FOC 2007)?
 - As determined using timed swim data?
 - As determined using transect data?
- What was the age structure of the population, as derived from size structure, using age-length keys developed from Shepherd et al. (2000)?

Relative density

- What was the relative density of abalone (#/minute) by site, study area, and size class (juvenile, adult, and all abalone combined)?
- Did the relative density of each size class vary at the spatial scale of sites within a study area?
- Was the relative density of each size class greater at Gravina Island than at Meares Pass, consistent with greater presumed predation by sea otters at Meares Pass?
- For Meares Pass only, was the relative density of each size class greater in 1980–1981 than 2016, consistent with anecdotal information and commercial catch data?

Absolute density

- What was the absolute density of abalone ($\#/m^2$) by site, study area, and size class (juvenile, adult, and all abalone combined)?
- Did the absolute density of each size class vary at the spatial scale of sites within a study area?
- Was the absolute density of each size class greater at Gravina Island than at Meares Pass, consistent with greater presumed predation by sea otters at Meares Pass?
- Were site-specific absolute densities indicative of a "healthy" population in each study area?
- Were site-specific absolute densities $< 0.2/m^2$ (a commonly cited threshold density for recruitment failure in some abalone species)?
- Was the site-specific absolute density of large adult (≥ 100 mm) abalone $\geq 0.1/m^2$, as specified in Canada's recovery strategy?
- What was the relationship between relative and absolute density estimates for in-common sites?

In this paper we defined the term *population* as a statistical population, not a true biological population. We defined the term in this manner because the boundaries of our study area were arbitrary, the entire depth range and habitat of the biological population was not surveyed, and most importantly, our study areas and sites non-randomly targeted locations with high abalone densities. Specifically the statistical population of interest was limited to abalone occurring in a 4 m wide strip from 0 to 9.1 m depth range (relative to the Mean Lower Low Water tidal datum, MLLW) at each site that were accessible to our sampling methods (i.e., not under rocks or anywhere that required invasive sampling to observe). Therefore, all absolute density metrics should be considered indices of abundance.

STUDY AREA AND SITE SELECTION

Study areas were chosen based on the following considerations, in approximate order of importance: evidence for a significant extant and, or, historical abalone population (Figure 1), logistical feasibility (e.g., amount of travel time required, ease of access in inclement marine weather), history of sea otter re-occupation (one study area recolonized by sea otters, one not), availability of historical fishery-independent survey data (to guide site placement and provide the basis for historical comparisons), and importance of fishing grounds (from a current/former cultural and former commercial fishing perspective). The study areas were, by necessity, located in areas that were open to legal subsistence and personal use harvest.

The focal locations of this study were southern Gravina Island near the city of Ketchikan, and Meares Pass, south of the city of Craig (Figure 2). These areas were chosen because of existing or historical abalone populations, a nearby community with a history of abalone harvest (Mills 1982), different histories of sea otter occupation (Hoyt 2015), and logistically feasible access within an otherwise remote archipelago. The study locations were characterized by an abundance of rocky shore habitat, diverse underwater topography, productive macroalgal communities (Meares Pass only), a shallow seafloor, and a range of wave exposures. There has been a long history of subsistence/personal use and commercial abalone harvest in both of these areas, although commercial harvest was discontinued in all of Southeast Alaska in 1996. Sea otters recolonized the area around the Meares Pass study area ca. 2010–2011 (Hoyt 2015) but have not recolonized the Gravina Island study area.

Within each study area, index site selection was guided using existing information. We reviewed ADF&G's historical dive survey data (Figure 3) to identify where and in what abundance abalone have been observed previously. Abalone densities were opportunistically reported in the red sea urchin and red sea cucumber datasets, but there was no standardization for reporting. These datasets are described in detail in Appendix A and included abalone surveys (1975–1997), red sea urchin surveys (1991–2014), and sea cucumber surveys (1990–2013).

The minimum number of sites targeted for sampling in each study area was 10, but more sites were selected in case time allowed. Index sites within each study area were arbitrarily assigned a priority using the following criteria, in descending order of importance: maximum relative density (for sites that were sampled during multiple years), logistical feasibility of sampling in the event of heavy seas, number of years surveyed, and proximity to other sites. These criteria were the same for both the abalone dataset and the combined sea cucumber and sea urchin dataset.

In the Meares Pass study area, dedicated abalone surveys were conducted at 29 sites in 1980, 1981, 1986, and 1997 (Figures 4 and 5), with some sites surveyed multiple times. Of these, 23 index sites were chosen and prioritized for sampling (Figure 6). In the Gravina Island study area, dedicated abalone surveys were conducted during 1978, 1979, 1980, 1981, and 1989 at four sites (Figure 7). There were not enough historical abalone survey sites on Gravina Island to meet our objective of 10 index sites per study area, and these sites were dispersed, so these surveys were used secondarily for site selection. The sea urchin and sea cucumber survey data provided greater spatial (Figure 7) and temporal (1994–2015) coverage of the Gravina Island shoreline, especially along the southern portion. The relative abundance index of abalone was also high in the southern portion (Figure 7), so index sites were concentrated in this area. A total of 23 index sites were chosen and prioritized accordingly (Figure 8).

METHODS

We applied a two-pronged approach to achieve the multiple objectives of 1) obtaining a “snapshot in time” of key abalone population metrics in two widely-spaced areas of historical abalone abundance, 2) using logistically feasible, repeatable methods so that the locations surveyed may be surveyed again in the future and serve as long-term monitoring sites, and 3) calibrating historical survey methods with modern repeatable methods to permit comparison of new data with historical data dating to 1980, the peak of the commercial abalone fishery. Our approach involved an unstructured timed search in which relative density and length frequency data were obtained using a method (timed swim) similar to the one used historically, and a more rigorous and repeatable transect/quadrat method to obtain absolute density and length frequency. Both methods were conducted in the same immediate vicinity at each site, using the same planned geographic coordinates as starting points.

FIELD SAMPLING METHODS

Timed Swim

A single relative density (i.e., timed swim) survey was performed at each index site by a two-person dive team. One diver (TDW) was the designated observer for all surveys, and the other diver served as safety diver and timekeeper. The primary objective of the observer was to count and measure as many abalone as possible within a 30-minute search period. The time taken to measure abalone was not included in the 30-minute search period in an attempt to replicate the historical sampling methods as much as possible. Historically, abalone were collected and brought to the surface for measurement, but we chose to minimize the risk of injury by eliminating the processes of collection, transportation, topside measurement, and replacement. The search image size of ≥ 50 mm along the maximum shell dimension was also chosen in order to approximate the assumed search image size assumed for historical abalone surveys. All abalone observed were counted and measured, regardless of size. The observer used a mostly unstructured search pattern in which they had few rules to abide by (e.g., swimming speed or direction). The only instructions and restrictions the observer had to follow were to begin the search between 3 and 5 m depth (MLLW), search the immediate area around any abalone found for other abalone, not invasively sample (e.g., turning over or moving rocks), not use a flashlight, and not search any deeper than 21 m deep (uncorrected to MLLW). The quality of the data, therefore, was dependent upon the observer’s search effectiveness, knowledge, experience, and intuition of abalone behavior and preferred habitat.

When the observer found an abalone, the search time was paused using a stopwatch by the buddy diver, and the observer measured the abalone using Vernier calipers across the longest shell dimension (Figure 9). When abalone were inaccessible (e.g., deep in crevices), the observer estimated the length and noted that the measurement was an estimate. The recorder also recorded the uncorrected depth (i.e., not corrected to MLLW) in feet. When finished and ready to proceed, the timekeeper then restarted the stopwatch and the observer continued searching. This procedure was repeated until the search was terminated at 30 minutes. The starting and ending geographic coordinates of the dive were recorded using Global Positioning System units with the Wide Area Augmentation System activated. The field protocol and field datasheet that was used for relative density surveys is in Appendix B.

Transect

A single transect was performed at each site. Transects were oriented perpendicular to the shoreline from 0 to 9.1 m depth (MLLW) (Figure 10). This depth range was chosen because it included the majority of the depth distribution for pinto abalone (Rothaus et al. 2008). A series of up to thirty 1x4 m² quadrat subsamples were placed along the transect at 0.3 m depth increments. Each 1x4 m² quadrat consisted of a contiguous bloc of four 1 m² quadrats oriented perpendicular to the transect. In practice, less than thirty 1x4 m² quadrats were sampled per transect due to tidal elevation change during a dive and unworkable wave surge in very shallow water. Because of time constraints, no hardware (e.g., eye bolts, lead line) was installed to permanently mark the exact location of the transect; instead, the start and end points of each transect were recorded from a high-resolution Geographic Positioning System (GPS). We anticipated that the precise coordinates obtained from the GPS would provide sufficient accuracy for transect relocation in the future.

At each index site, a transect meter tape was temporarily anchored to the seafloor and divers deployed the tape along the seafloor in as straight a line as possible. Working from offshore to onshore, a two-diver team enumerated and measured all abalone observed within 1 m² PVC quadrats. The target search image size was ≥ 30 mm shell length. Using Vernier calipers, divers measured all abalone within their respective quadrats that were accessible regardless of size. The length of inaccessible abalone was estimated to the nearest millimeter and flagged as an estimate on the datasheet. Divers used flashlights to illuminate dark areas (e.g., crevices) when necessary, and no invasive sampling was allowed. Ancillary data was collected for substrate type, vegetation type and cover, and depth within each diver's 1x2 m² portion of the 1x4 m² quadrat. The field protocol and field datasheet that was used for absolute density surveys is in Appendix C.

STATISTICAL METHODS

All data analyses were performed using the Real Statistics Resource Pack software (Zaiontz 2015), unless stated otherwise. When applicable, diagnostics were evaluated to check assumptions and assess the validity of analyses; diagnostics included variance equality, distribution symmetry and normality. Parametric statistical tests were used when possible, and non-parametric tests were used when assumptions were moderately to severely violated. Effect sizes (defined as standardized measures of the magnitude of an effect) were reported for most statistical tests to facilitate the interpretation of biological significance in addition to statistical significance, and to facilitate comparisons with other studies. The correlation coefficient r was

used as the measure of effect size (calculations varied and are specified below for specific tests). Effect size (r) values of 0.1, 0.3, and 0.5 were classified as small, medium, and large, respectively, per convention (Zaiontz 2015). Sample sizes for many tests were below the minimum recommended for using the normal distribution in hypothesis testing, but nevertheless these statistics were reported in order to obtain estimates for effect sizes.

Length Frequency

Descriptive statistics were calculated and summarized for length frequency data for each combination of study area, method, and metric. Individual length data were summarized into 5 mm bin sizes and length frequency distributions were plotted for each combination of study area (histogram), site (bubble plot), and method (histogram and bubble plot). A bin size of 5 mm was used because it is a common size reported in abalone research (e.g., Rogers-Bennett et al. 2013) and management plans (e.g., CDFW 2005). We did not test for differences in length frequency distributions among sites within a study area because of small sample sizes (i.e., individual lengths). To test whether the length frequency distributions were different for any combination of study area and method (2 methods x 2 study areas), four independent pairwise comparisons were made using Kolmogorov-Smirnov (K-S) two-sample tests.

K-S tests were used because they are a powerful test of whether two samples come from the same underlying distribution, and they have been used commonly to test for differences in length-frequency distributions in pinto abalone specifically (e.g., Rogers-Bennett 2013). K-S tests were performed with a global $\alpha = 0.05$ and each test was adjusted for error rate using the Bonferroni correction factor ($\alpha = 0.008$). For Meares Pass only, length frequency distributions were compared among years (1980–1981, 1986, and 2016) using three independent pairwise Kolmogorov-Smirnov two-sample tests. Data input was restricted to sites in which data were available for both 1980–1981 and 2016; not all sites had data for 1986. Tests were performed with a global $\alpha = 0.05$ and each test was adjusted for experiment-wise error rate using the Bonferroni correction factor ($\alpha = 0.017$).

To test whether a relationship existed between abalone length and depth, two simple linear regressions were performed. Linear regressions were used because they are a simple, common, easily understandable test, and we expected any relationship between the two variables to be linear in shape within the domain of the depth range sampled. One regression test used timed swim data and the other used transect data; data from both study areas were combined for each test. The replicate was an individual observation in which both abalone length and depth were recorded. Uncorrected depths recorded by the observer were corrected to MLLW by adding the tide correction from the beginning of the dive.

Alaska does not have a management or recovery plan for pinto abalone, so we assessed the status of pinto abalone in Southeast Alaska using criteria in management plans developed by the California Department of Fish and Wildlife (CDFW 2005) and by Fisheries and Oceans Canada (FOC 2007). The first criterion for recovery in the CDFW (2005) Abalone Recovery and Management Plan (ARMP) was “broad size distribution of the former abalone range”. To assess this criterion, intermediate and large size classes were designated and abalone lengths were binned by 5 mm increments. A population was determined to have met the criterion when 90% and 25% of the length bins within the respective intermediate and large size classes had counts ≥ 1 . For the seven abalone species in their jurisdiction, CDFW (2005) based threshold values

between the small/intermediate and intermediate/large size classes on the size below which abalone are usually cryptic and not easily assessed, and the minimum legal size, respectively. They defined the intermediate and large size classes for pinto abalone to be 76–102 mm and >102 mm, respectively. We have observed that abalone >50 mm were generally emergent (i.e., not cryptic), and ADF&G’s minimum legal size for the recreational, personal use, and subsistence fisheries has been 89 mm for many years, so we redefined the intermediate and large size classes to be 51–90 mm (8 bins) and 90–165 mm (15 bins), respectively. The maximum length in the large size class (165 mm) was set based on the largest pinto abalone on record (Breen 1980). The length-based objective in the Fisheries and Oceans Canada recovery strategy (FOC 2007) was that the percentage of sites in an area with large adult (≥ 100 mm) abalone was $\geq 40\%$.

To describe the estimated age structure of the abalone populations at Gravina Island and Meares Pass, age-length keys were constructed from historical data that was originally collected for an abalone ageing study in Southeast Alaska during 1998 (Shepherd et al. 2000). We chose to estimate the age structure using this method because appropriate local data were readily available, more direct, and required less assumptions than for more complicated methods in which ages were inferred from length frequency distributions (e.g., Fournier and Breen 1983). Shepherd et al.’s (2000) Ridge Island study site was located very close to our Meares Pass study site, and their Gravina Island site was very close to our Gravina Island site, so we considered comparisons of their data with ours to be appropriate. We applied this key to the 2016 abalone length data using methods described in Ogle (2016). Statistical analysis was performed using R software (R 2017) and the FSA package for R (Ogle 2017).

Relative Density

For each timed swim dive, relative density was calculated as the number of abalone counted/minute of searching/diver/dive. Only one diver collected data and one dive was performed per index site. Relative density data were summarized using descriptive statistics for each site, study area, and for each of three size classes: juvenile (<50 mm), adult (≥ 50 mm), and all abalone combined. There was no within-site spatial or temporal replication, and therefore no estimate of variability was possible for an index site.

To test whether the relative density at Gravina Island was greater than at Meares Pass for each size class, we used both a one-tailed two-sample Mann-Whitney U test for independent samples and a Mann-Whitney Exact test. Statistical comparisons were made using three one-tailed two-sample Mann-Whitney U Tests for independent samples because the assumptions underlying the planned parametric one-tailed two-sample t -tests were substantively violated—specifically, the assumptions of distribution symmetry, equal variances, and, to a lesser extent, normality. Relative density data were highly skewed at the spatial scale of sites within study areas. Data transformations (e.g., $\ln(x) + 1$) were attempted but the diagnostic results were not substantively different and the assumptions were still violated, so for simplicity the raw data were used in all analyses. The Exact test was performed because no assumptions about the distribution of the data were required, and the sample size was small enough ($n < 25$) to permit its computation. A “tie correction” was used to accommodate multiple rank ties in the datasets, and may have resulted in conservative p -values. To account for inflation of experiment-wise error rate associated with multiple tests, α was adjusted using a Bonferroni correction.

To test whether the relative density of all abalone sizes combined was greater in 1980–1981 than 2016 at Meares Pass, we used a one-tailed Wilcoxon Signed-Rank Exact Test for Paired Samples ($\alpha = 0.05$). The one-tailed Wilcoxon Signed-Rank Exact Test for Paired Samples was used instead of a paired t -test because one of the key assumptions for parametric testing (distribution symmetry) was violated, along with a lesser violation of unequal variances. The unit of replication was a dive site that was surveyed during both years. Surveys conducted in 1980–1981 were combined into one time category for purposes of this comparison. The single in-common site at Gravina Island surveyed historically was not analyzed due to lack of spatial replication.

Absolute Density

Absolute density data from transects were summarized using descriptive statistics for each site, study area, and for each of three size classes: juvenile (<50 mm), adult (≥ 50 mm), and all abalone combined. The density of abalone per square meter was estimated for each transect as:

$$D = \frac{1}{Qkn} \sum_{i=1}^n c_i \quad (1)$$

where:

D = estimated number of pinto abalone per square meter,

i = quadrat index,

c_i = count of abalone in each quadrat i from 1 to n ,

Q = quadrat length (along-transect dimension) = 1 m,

k = quadrat width (across-transect dimension) = 4 m, and

n = number of quadrats.

To test whether the absolute density at Gravina Island was greater than at Meares Pass for each size class, we used both a one-tailed two-sample Mann-Whitney U Test for independent samples and a Mann-Whitney Exact test. Non-parametric Mann-Whitney U Tests for independent samples (Exact version) were used for all comparisons because input data severely violated several assumptions of parametric testing (i.e., symmetry, equal variances, normality). Absolute density data were highly skewed at the spatial scale of 1 m² quadrats (the grain size of the sampling unit), 1x4 m² quadrats within sites (i.e., four aggregated 1 m² quadrats at each transect depth increment), and sites within study areas. There were a high proportion of zero counts for individual 1 m² quadrats. Data transformations (e.g., $\ln(x) + 1$) were attempted but the diagnostic results were not substantively different and the assumptions were still violated, so raw data were used in all analyses for simplicity of interpretation. Results from the normal version of the test were reported in order to calculate the approximate effect sizes of the relationships. The Exact test was performed because no assumptions about the distribution of the data were required, and the sample size was small enough ($n < 25$) to permit its computation. A “tie correction” was used to accommodate multiple rank ties in the datasets, and may have resulted in conservative p -values. To assess statistical significance, the alpha value was adjusted using a Bonferroni correction to account for inflation of experiment-wise error rate associated with multiple tests.

To test whether the site-specific density of adult (≥ 50 mm) abalone was significantly different than a hypothesized median density of $0.2/\text{m}^2$ associated with population collapse and recruitment failure, we used a series of one-sample Wilcoxon Signed-Ranks Tests. Several assumptions of parametric testing were violated substantially (i.e., symmetry, equal variances, normality), so a non-parametric one-tailed, one-sample Wilcoxon Signed-Ranks Test was used instead of a paired t test for each site-specific comparison. The hypothesized median density of $0.2/\text{m}^2$ used here was substituted for the mean density threshold density for recruitment failure estimated by Babcock and Keesing (1999), Shepherd and Brown (1993), and used as a Minimum Viable Population density for red abalone in CDFW's AMRP (CDFW 2005). Because the reason for these tests was to inform conservation and management of the species, each test was set to $\alpha = 0.05$ instead of being adjusted for experiment-wise error rate in order to reduce the probability of Type II error (false negative results). Tests were performed for each site because we expected aggregation densities to vary substantially among sites, and the spatial scale of sites coincided more with the spatial scale of abalone aggregations than did the spatial scale of study areas.

To investigate the relationship between absolute density and relative density, we used simple linear regression, using index site as the replicate. Linear regression was used because it is a simple, common, easily understandable test, and we expected a linear relationship between the two variables.

RESULTS

Logistics

Surveys were conducted over two days in each study area during July 2016 (Meares Pass: July 10–11; Gravina Island: July 24–25). Ten historical index sites were re-established in the Meares Pass study area, one historical site was re-established in the Gravina Island study area, and 14 new index sites were established in the Gravina Island study area (Table 1, Figures 11–12, and Appendix D). Transect surveys were conducted at each site, and timed swim surveys were conducted at a subset of these sites (Table 1). Diving conditions were adequate in both study areas but were more favorable at Gravina Island than Meares Pass with respect to wave surge and underwater visibility. Six unique divers collected transect data and one unique diver collected timed swim data (Table 2); all divers had previous experience surveying abalone. Timed swim durations ranged from 31 to 75 minutes, except for site 104-30 #17, where the dive was aborted after 17 minutes due to poor underwater visibility.

Length Frequency

Abalone were present at all sites surveyed in each study area. They were recorded during all timed swim dives except for one site in Meares Pass (104-30 #17), where the dive was aborted. Abalone were present in transect counts at all sites in the Gravina Island study area and all but one site (104-30 # 102) in the Meares Pass study area. Abalone sample sizes were much larger for timed swims than transects, even though the number of sites surveyed by transects exceeded the number surveyed by timed swims (Table 3). Sample sizes were also much larger for Gravina Island than Meares Pass, regardless of method (Table 3). The sample size of abalone length measurement/estimates from timed swims at Gravina Island ($n = 663$) exceeded the sample size of $n = 510$ recommended by Thompson (1987) for 95% certainty that the proportions within each sample size class are within 5% of the true population proportion (assuming the proportions are

multinomial in nature). The sample size for transects at Gravina Island ($n = 456$) was close but did not meet this threshold. The percentage of abalone lengths estimated [due to inaccessibility] ranged between 4–15% for timed swims in both study areas and for transects at Gravina Island, but was substantially higher (41%) for transects at Meares Pass (Table 3). This result may have been related to the proportion of abalone recorded as cryptic for timed swims at Meares Pass vs. Gravina Island (58% and 11%, respectively; Table 3), but the sample size of behavioral observations was too small for transects in Meares Pass to evaluate.

Abalone length frequencies differed at a spatial scale of sites (hundreds of meters) at Gravina Island for both timed swims and transects (Figure 13). These differences were readily apparent in the timed swim data from sites 101-27 #14, 101-27 #24, and 101-29 #1 (Figure 13). The number of abalone observed per site at Meares Pass was too small to discern patterns with any confidence (Figure 14). Sites were spaced much closer in Meares Pass than Gravina Island, which would have made determination of site-specific differences in this area more unlikely in any case.

The length frequency distributions were unimodal for Gravina Island and bimodal for Meares Pass in both the timed swim and transect datasets (Figure 15). The trough between modes at Meares Pass was evident in the 36–40 mm size class for both methods. For Gravina Island, the mode was shifted by approximately 10 mm from 31 to 35 mm in the timed swim datasets to 41–45 mm in the transect dataset. In general, the size structure was shifted toward larger size classes (>75 mm) at Gravina Island, especially in the timed swim dataset, whereas smaller size classes (<31 mm) were relatively more predominant at Meares Pass.

Abalone lengths (both methods combined) ranged from 2 to 115 mm (Figure 15). The maximum lengths differed substantially between study areas (96 vs. 115 mm for Meares Pass and Gravina Island, respectively), although there were smaller sample sizes at Meares Pass. Visually, there was no apparent truncation of size classes larger than the legal size limit for personal use and subsistence fisheries (89 mm) at Gravina Island (Figure 15); the small sample size of abalone lengths for Meares Pass made any possible truncation (if present) difficult to determine.

The length frequency distributions were significantly different between study areas for both methods, and between methods for Gravina Island only (Table 4). Input data for the methods tests were only from sites in which timed swims and transects were both performed. Sample sizes were substantially smaller at Meares Pass than Gravina Island for both methods, especially for transect data. Sampling depths were shallower in general for timed swims than transects (Figure 16), and there was no relationship between abalone length and tide-corrected depth using either timed swim and transect data (Tables 5–6).

The length frequency distribution from timed swims at Meares Pass during 2016 was significantly different from historical samples collected using similar methods at the same sites during 1980–1981 and 1986 (Table 7, Figure 17), despite the small sample size and associated low statistical power in 2016. The historical surveys in 1980–1981 and 1986 were also significantly different from each other (Table 7). Relative to historical data, the size distribution in 2016 was shifted toward smaller size classes, and the bimodal distribution contrasted to the unimodal distributions evident in both 1980–1981 and 1986. Very few abalone less than 26 mm length were recorded in the 1980–1981 and 1986 datasets, in contrast to a substantial portion of the abalone from the 2016 survey in this size class. It was impossible to determine whether the

scarcity of abalone <26 mm in the historical samples reflected sampling bias toward larger individuals or a true difference in the size structure of the population.

The abalone population sampled in the Gravina Island study area during 2016 fully met the California Department of Fish and Wildlife's recovery Criterion 1 in CDFW's ARMP (CDFW 2005). For the intermediate size category, 100% (8 of 8) of the 5 mm size bins had counts greater than zero for both timed swims and transects. For the large size category (defined here as 91–165 mm), 27% (4 of 15) of the 5 mm size bins were non-zero for the timed swim dataset, and 33% (5 of 15) of the 5 mm size bins had counts greater than zero for the transect dataset. For the Meares Pass study area, the 90% criteria for the intermediate size category was met using the timed swim data but not the transect data (100% and 88%, respectively), and the 25% criteria for the large size category was not met using data from either method (13% and 7%, respectively).

Whether or not the abalone population at the Gravina Island study area met the minimum site occupation rate of 40% for large adult abalone (defined as ≥ 100 mm) specified in Canada's recovery strategy for northern abalone (FOC 2007) depended on the method used to obtain the length data. For timed swims, 44% of sites met the criteria whereas with transects, only 33% met the criteria. The density of large adult abalone in the Gravina Island study area were below the minimum threshold of $0.1/\text{m}^2$ outlined in the same plan at 12 of the 15 sites surveyed using the transect method. There were no abalone ≥ 100 mm observed in the Meares Pass study area using either method.

Abalone ages were estimated using the length frequency data collected in 2016, in concert with age-length keys developed from a dataset collected in the 1998 by Shepherd et al. (2000) from sites throughout Southeast Alaska ($n = 509$). Only lengths from timed swims were used for age estimation because the sample size ($n = 661$ for Gravina Island and $n = 132$ for Meares Pass) was substantially greater than for transects. Estimated ages ranged from 1 to 12 years for Gravina Island (peak age = 2) and 1–6 years for Meares Pass (peak age = 1) (Figure 18).

Relative Density

The relative density observed during timed swims varied substantially by size class and among sites within study areas (Figure 19). Data were aggregated by study area for each size class, and Gravina Island had consistently higher densities than Meares Pass for each size class assessed (Figure 20). The median relative density was significantly greater at the Gravina Island study area than at Meares Pass for all three size classes tested, as hypothesized, when assessed for significance without correcting for the inflated experiment-wise error rate ($\alpha = 0.05$; Table 8). The effect sizes were large ($r \geq 0.5$) for all comparisons. When the experiment-wise error rate was taken into account ($\alpha = 0.017$), the results were nearly the same but the difference in juvenile relative density was non-significant according to the exact test.

The relative density was substantially lower at every site in Meares Pass for each survey since 1980–1981 (Figure 21). Two sites were surveyed in 1997 but were not considered here because the small sample size was too small to be meaningful. Among in-common sites, there was an 89% decrease in relative density from 1980 to 81 to 2016, and an 83% decrease from 1986 to 2016. The assumption of a monotonic trend between 1986 and 2016 was tenuous because of a combination of the low resolution of the time series and the re-colonization of sea otters between surveys, so we only tested for a difference in relative density between 1980–1981 and 2016. All nine sites surveyed at Meares Pass in 1980–1981 were also surveyed during 2016. The median

relative density was significantly less in 2016, with a correspondingly large effect size (Table 9, Figure 22).

Absolute Density

As with relative abundance, the absolute density of abalone varied substantially among size classes and sites within each study area (Figure 23). Study area-specific median densities were consistently higher in the Gravina study area than Meares Pass for each size class, but sampling distributions showed substantial overlap (Figure 23). Statistical comparisons of absolute densities between study areas (H_A : Gravina Island > Meares Pass) by size class confirmed that there were no significant differences for any size class (Table 10).

The mean density of adults (and SE) for each study area was $0.29/\text{m}^2$ (0.08) and $0.17/\text{m}^2$ (0.03) for Gravina Island and Meares Pass, respectively. At Gravina Island, median densities of adult abalone (≥ 50 mm) were below the density threshold of $0.2/\text{m}^2$ for recruitment failure at 6 of 15 index sites, but only two sites were significantly below the threshold (Table 11). At Meares Pass, 6 of 10 index sites were below the threshold, but only three significantly so (Table 11).

Relative Density vs. Absolute Density

There was no statistically significant relationship between density estimation methods, as tested using linear regression (Table 12, Figure 24). One outlier data point with high leverage was primarily responsible for the relatively low p -value (0.07).

DISCUSSION

All objectives in the original proposal were accomplished as planned. “Permanent” index site establishment (or re-establishment) was successful, and the proposed minimum of 10 sites within each study area was met within the four funding days allotted for the surveys. Historical abalone survey data were compiled and used to guide placement of all ten index sites in Meares Pass, and one of the 15 index sites in the Gravina Island area. Historical sea cucumber and sea urchin survey data were used to place the remaining index sites at Gravina Island. Some of the field and analysis methods used in the study were slightly different from those described in the study proposal. Changes were made only when it was determined that doing so would not substantively change the intent of the study (e.g., stock assessment vs. long-term monitoring site establishment), and when it would result in an overall improvement. Some methods used in the study were additional to what was proposed (e.g., analysis of time-series using historical data), whereas some methods listed as optional in the proposal (e.g., distance sampling) were not done due to lack of available time. The methods were reproducible and were sufficient to assess abalone spatial distribution, density, size distribution, and habitat at site- and area-specific spatial scales. A comprehensive evaluation of the methods used in this study is included in Appendix E.

The current status of abalone populations in each study area was somewhat ambiguous, with independent lines of evidence (absolute density and length frequency, respectively) suggesting both a risk of population collapse as well as self-sustaining populations. When evaluated against Canada’s recovery plan criteria (40% site occupation rate for abalone ≥ 100 mm, and absolute density $\geq 0.1/\text{m}^2$ for abalone ≥ 100 mm; FOC 2007), the abalone population at Meares Pass failed both tests. The results were ambiguous for the occupancy rate test at Gravina Island, depending on whether the timed swim or transect dataset was used. At Gravina Island, 80% of the sites were below the $0.1/\text{m}^2$ threshold for large adults, although this was not tested statistically. While

recovery goals and criteria are undoubtedly useful metrics, Canada's metrics were tailored to the sizes and densities of abalone populations in their jurisdiction when their plan was developed. We were more concerned with what the universally applicable risk of population collapse was. Therefore, we gave more weight to comparisons of our observed densities vs. theoretical and empirical threshold absolute density values for stock collapse in other species of abalone reported in the literature. At 40%, the percentage of sites with adult densities below the $0.2/\text{m}^2$ threshold at Gravina Island was higher than expected, although only 13% of sites were significantly less, statistically. At Meares Pass, 60% of sites were below threshold, with 30% significantly less. The statistical power of our analysis was reduced by the low absolute density values and high variability of the data, as well as our forced reliance on nonparametric tests. Nonetheless the overall pattern at the site level of a high failure rate, especially for Meares Pass, was fairly clear. The absolute density for each study area (all sites combined) was quite close to the $0.2/\text{m}^2$ threshold as well.

The low absolute densities were cause for concern, especially if either the true threshold density for stock collapse is higher than $0.2/\text{m}^2$ or our calculated densities were actually lower than reported. Shepherd and Brown (1993) showed the onset of long-term recruitment failure for *H. laevigata* in Australia when adult densities fell below $0.3/\text{m}^2$. This corresponded fairly closely to the upper threshold density of $0.33/\text{m}^2$ used by Rothaus et al. (2008) to conclude pinto abalone in the San Juan Islands of Washington experienced recruitment failure due to the Allee effect. Furthermore, the definition for an "adult" abalone in this study was liberally defined as ≥ 50 mm. The 50 mm length was primarily based on observations of sexual maturity in the Sitka area (Paul and Paul 1981). However, Larson and Blankenbeckler (1980) reported maturity at 51–64 mm in southern Southeast Alaska (cited in Woodby et al. 2000), and Campbell et al.'s (2003) review and study of abalone in British Columbia indicated that 50 mm was the size at 50% maturity, with 70 mm corresponding to 100% maturity. If we had defined an adult more conservatively per Larson and Blankenbeckler (1980) or Campbell et al. (2003), our adult density estimates would have been even lower.

The absolute density results were especially troubling because both study areas were former sites of abalone abundance, and the study sites within each area were chosen because they had the highest historical abalone densities in the area relative to other nearby sites investigated. In particular, Gravina Island is one of the places in Southeast Alaska where one would least expect abalone populations to be in peril. This area probably has not had resident sea otters for over 100 years (the end of the sea otter fur trade), it has been closed to commercial harvest for over 20 years, and subsistence/personal use harvest has presumably been light (see treatment of "fishery effects" below).

The evidence for self-sustaining populations came exclusively from the length frequency data. The length frequencies observed at Gravina Island met CDFW's (2005) recovery criterion 1, but the criterion was not met at Meares Pass, possibly because of size-selective predation by sea otters on the largest abalone. There were clear indications of recent recruitment in both study areas. All of the histogram size class bins in our study between 6 and 35 mm were occupied in both areas for each method. Shepherd et al. (2000) considered abalone with shell lengths between 13 and 25 mm to be age 1 (all study sites combined). According to regression analysis by Shepherd et al. (2000), mean abalone shell length at age 1 was between ~19 and 23 mm at moderately wave-exposed outer coastal sites, and between 30 and 35 mm in non-outer coastal sites. The evidence for recent recruitment was not wholly unexpected because similar patterns

were observed for abalone populations in Sitka Sound (Bell et al. *in prep*), where abalone have been subjected to sea otter predation and human harvest pressure for many years. However, Sitka Sound is somewhat unique in several ways (e.g., oceanography, proximity of abalone aggregations to urban area, sea otter density gradient away from urban area), so it was unknown whether results found there would also be found elsewhere.

The lack of distinct peaks and troughs in the length frequency histogram for Gravina Island also suggested consistent annual recruitment for at least the last several years (modes become compressed for older age classes; Shepherd et al. 2000). Recruitment appeared to be less consistent at Meares Pass. There was a trough in length frequencies at Meares Pass in the 36 and 40 mm size class in both the timed swim and transect datasets, which suggested that the age-2 year class was under-represented, according to the estimate from length frequency decomposition for Ridge Island in Shepherd et al. (2000). It was unlikely that this trough at Meares Pass was an artifact of small sample size because it was also evident in the transect dataset. Reduced recruitment stability at Meares Pass would be consistent with the expectation for small or low-density abalone populations to exhibit increased recruitment variability (Stephens et al. 1999), which could be especially problematic for the long-term viability of the population if the much-reduced number of age classes in this area is not an artifact of small sample size.

Possible reasons for the apparently contradictory indicators of population status fell into two classes: survey/sampling bias and biological. The most obvious potential explanation was that our absolute density estimates were biased low. This could have been due to the survey design, the size class definition of adult abalone (discussed previously), inadequate search effectiveness of observers, or a substantial number of cryptic, undetected abalone. The absolute density estimates were certainly lower and had greater variability than they would have been if transects had been oriented parallel to the depth contour within the optimal abalone depth range, as they were in our recent Sitka Sound study (Bell et al. *in prep*). The perpendicular orientation forced sampling across the primary gradient of variability in abalone density, which was usually greatest in a narrow depth band between approximately 2–5 m MLLW. Although the perpendicularly oriented transect captured a better estimate of the density of the population than a single transect parallel to the depth contour would have, a single parallel transect within the optimal depth zone would have better captured the most abundant portion of the population. With respect to potential sampling bias, all survey divers had previous experience doing abalone surveys, but a subset were accustomed to surveys for other species (e.g., sea cucumbers), which were conducted at a much more rapid pace than the slow, methodical pace required for abalone surveys. Therefore, it was possible that the abalone survey pace was too rapid to detect all potentially detectable individuals within quadrats.

The optimistic potential biological explanation for the contradiction in population status indicators was that the $0.2/\text{m}^2$ (range: $0.15\text{--}1/\text{m}^2$) threshold for stock collapse described for other abalone species may be higher than the threshold for pinto abalone, or at least for pinto abalone in Alaska. For purposes of evaluating reproductive potential, the density of adults within spawning aggregations is more important than non-spawning density, the latter is presumably what has been measured in most field studies (except Babcock and Keesing 1999). Pinto abalone can move quickly (personal observation), so it is possible that they use this mobility to aggregate more effectively during spawning events than other abalone species. Unfortunately, however, a lower stock collapse threshold for pinto abalone seems unlikely, given the supporting evidence

for the $0.2/\text{m}^2$ threshold from the San Juan Islands in Washington. The mean density of abalone populations at 10 sites there declined steadily from $0.18/\text{m}^2$ to $\sim 0.01/\text{m}^2$ over the period 1992–2013, and there was little evidence for successful recruitment throughout the entirety of the time series (Rothaus et al. 2008; Bouma et al. 2012; Busch et al. 2014). Further, recruitment failure in Washington was likely at the outset of the study in 1992 when mean densities were at $0.18/\text{m}^2$ (Rothaus et al. 2008), which suggested that the mean density threshold is some unknown amount higher. This seems likely given that 50% of the 10 sites in Washington had densities between approximately $0.26\text{--}0.32/\text{m}^2$ in 1992. These findings are especially concerning as they apply to abalone in Alaska, because the decline occurred in the absence of sea otters or legal fisheries of any kind, both of which Alaska has.

At our Meares Pass study area, we observed what may have been a long-term decline in relative density similar to the decline in absolute density in Washington, but a lack of temporal resolution in the time-series between 1986 and 2016 prevents any firm interpretation. There was a clear decline from 1980 to 1981 to 1986 that can safely be attributed to commercial fishing effects (there were no sea otters present during that period). The observed decline in relative density between 1986 and 1995 was similar in magnitude to the decline in total commercial catch and catch per unit effort over that same period (Woodby et al. 2000). However, relative density data gaps between 1986 and 2016 were especially problematic because key events such as the commercial fishing closure in 1995 and recolonization by sea otters in the 2000s were not captured. Although these data gaps prevented informed interpolation of potentially important shorter-term trends in the dataset, the overall difference in relative abundance between 1980–81 and 2016 was strikingly clear. What was unclear, however, was 1) whether or how the decline in relative density related to absolute density, given the lack of a significant relationship between the two metrics in this study; and 2) the relative importance of possible causes for the decline (e.g., growth or recruitment overfishing by the commercial fleet, sea otter predation, Allee effects).

While we cannot attribute causation for the decline over time at Meares Pass with any certainty, it was probably not due to harvest from personal use and subsistence fisheries. There was no obvious fishery effect visible in the length frequency histograms for the Meares Pass and Gravina Island study areas. A strong fishery effect would have been indicated by truncation of size frequencies in the histogram above the legal size limit of 89 mm, which has been in effect for many years. The absence of an obvious effect was not surprising for Meares Pass because of the small sample size, distance from a significant population center, and confounding presence of sea otters. However, we did expect to possibly see a fisheries effect at Gravina Island, where sea otters are absent and the area is in relatively close proximity to the city of Ketchikan, a significant population center in Southeast Alaska with a vibrant fishing community. The lack of an obvious effect that could be discernable from our data does not necessarily mean that there was no such effect, however. It would be difficult to confidently make a determination of a fisheries impact using either length frequency or density data without having a controlled experiment (e.g., areas both open and closed to human harvest near population centers where harvesting is known to occur), as well as a sufficient sample size.

The maximum lengths observed in this study (115 mm at Gravina Island and 96 mm at Meares Pass) were well below both the maximum length recorded for the species (165 mm; Breen 1980) and the maximum length of 137 mm observed in the Sitka area during abalone surveys in 2015–2016 (Bell et al. *in prep*). This was not surprising given the relatively small sample size of length

data collected during this study (especially for Meares Pass), which obviously has a strong effect on the likelihood of observing very large individuals. The smaller maximum length observed at Meares Pass was consistent with the expected effect of intense size-selective sea otter predation that is certainly occurring in that area (sea otters were observed on-site during sampling of several transects). However, the smaller maximum size at Meares Pass was inconsistent with the observation that pinto abalone grow faster in moderately wave-exposed areas with giant kelp (Sloan and Breen 1988), which was the case at Meares Pass but not Gravina Island. Although the Gravina Island study area could be considered to have moderate wave exposure, it was almost completely devoid of fleshy algae (including kelps) due to intensive grazing by red sea urchins (primarily) and abalone.

The maximum age estimated from length frequency data for abalone measured at Gravina Island during 2016 was very similar to the maximum age of 13 years found by Shepherd et al. (2000) in their complete dataset (all sites combined). Shepherd et al. (2000) also aged shells from seven captive abalone of known age, and found a maximum age of 19 years. The Committee on the Status of Endangered Wildlife in Canada postulated a maximum age for the species between 15 and 20 years (COSEWIC 2009) based on Shepherd et al.'s (2000) data, and the COSEWIC (2009) estimate was cited by Busch et al. (2014) as the most reasonable estimate of longevity. Based on the latter longevity estimations, our maximum age of 12 years for Gravina Island is reasonably close to the maximum age expected. Conversely, the maximum estimated age for abalone from Meares Pass in this study (6 years) was far less than the maximum expected age. This low maximum age was certainly due in part to the small sample size ($n = 132$ for timed swim datasets) and the associated lower likelihood of encountering large, old specimens, but we suspected that the more influential factor was probably size-selective sea otter predation.

CONCLUSIONS

There is sufficient direct and indirect evidence to indicate that the status of pinto abalone populations in southern Southeast Alaska warrants concern. The primary reason for this concern is the equivocal evidence for whether the populations within the areas studied are at risk of collapse. Length frequency-based data analyses suggested that the populations are not at high risk, but relative- and absolute-density based data analyses indicated that they are, especially for the Meares Pass study area. The presence of other risk factors exacerbates the risk of collapse. Alaska-specific risk factors include a large and expanding sea otter population, ongoing and unquantified personal use and subsistence fisheries, a lack of fishery-independent stock assessments or long-term monitoring data, and a legacy of insufficiently conservative management measures. Other reasons for concern are a collapsing population in Puget Sound despite 23 years of fishery closures and an absence of sea otters, as well as recent, unprecedented changes in ocean climate, chemistry, and food webs.

Nevertheless, the clear indication for recent and ongoing recruitment to the populations was encouraging, especially for the sea-otter occupied Meares Pass and Sitka Sound study areas. We expect abalone populations to remain at low levels, at best, in sea otter occupied habitats, and the densities we observed may simply be a new stable state. As long as recruitment remains strong, it is certainly possible for abalone populations to persist at low levels in the presence of sea otters, provided adequate microrefugia are available. What is more concerning is the uncertainty about why abalone populations have not recovered faster than they have in the Gravina Island area, despite the apparently strong recruitment.

It would be a tenuous assumption that the two small areas studied were representative of unsurveyed areas in the vast archipelago of southern Southeast Alaska, but from a conservative perspective this should be assumed until shown otherwise because it is currently the best available data. Further, it should be emphasized that the study areas included in this study were chosen because they were among the most important abalone harvest areas in their respective geographic domains historically, and the sites within these study areas were chosen because they had the highest historical densities of abalone. Therefore the areas studied represent our best estimate of the “best of the best”. If these areas truly do represent the best of the best extant abalone populations, then until more or better data/analyses are available it would be logical to assume that abalone populations in less historically successful locations are probably in poorer shape. Without recent surveys on a geographically expansive spatial scale, it is unknown whether this is the case. The knowledge gaps and uncertainties in the ESA status review (Busch et al. 2014; Woodby et al. 2000) and again here highlight the need for additional, timely studies. Without resolution to key questions and some form of feedback from long-term monitoring, we risk impairing the sustainability of this economically, culturally, and ecologically valuable resource.

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TABLES AND FIGURES

Table 1.—Summary of site- and method-specific logistics, sample sizes, and sample unit sizes. The site numbers of re-established historical index sites are shown in *italics*. Timed swim survey time included both searching and data recording time. The timed swim dive at site 104-30 #17 (Meares Pass) was aborted due to poor visibility and low light level, so data were not used in analysis.

Study Area	ADF&G Sub-district	Site #	Transects					Timed Swims		
			# Dives	Dive Time (min.)	Survey Time (min.)	# 1x4 m ² Quadrats	Area Swept (m ²)	# Dives	Dive Time (min.)	Survey Time (min.)
Gravina Island	101-25	26	1	69	55	10	40	1	54	51
	101-27	9	1	46	34	10	40	1	49	45
		10	1	64	44	10	40	1	54	46
		13	1	52	40	10	40	0	0	0
		14	1	62	45	10	40	1	72	68
		15	1	65	59	10	40	1	38	34
		16	2	85	76	8	32	1	76	75
		24	2	73	58	10	40	1	72	68
	101-29	1	1	68	57	10	40	1	68	61
		2	1	44	39	10	40	0	0	0
		3	1	61	55	10	40	0	0	0
		4	2	114	106	10	40	0	0	0
		5	1	42	22	10	40	0	0	0
		6	1	46	46	10	40	0	0	0
		108	2	94	61	10	40	1	52	48
Meares Pass	104-30	16	3	135	99	10	40	1	32	32
		17	2	112	103	8	32	1	17	17
		18	2	86	94	10	40	1	51	50
		19	2	137	117	9	36	1	58	34
		20	2	109	77	6	24	1	41	35
		21	1	78	60	10	40	1	58	47
		22	2	93	74	10	40	1	43	36
		23	2	108	96	9	36	1	59	36
		24	2	115	59	10	40	1	46	45
		102	1	58	50	10	40	1	41	31

Table 2.–Summary of dives by diver, method, and study area. All divers were affiliated with ADF&G except Lauren Bell and Taylor White, who were affiliated with the Sitka Sound Science Center. All divers who participated in transect dives collected data. For timed swim dives, Taylor White was the sole data collector; Carl St. John and Justin Breese served as dive buddies and timekeepers for these dives.

Diver Name	Initials	Gravina Island		Meares Pass	
		Transects		Transects	
		# of	Dive	# of	Dive
		Dives	Duration	Dives	Duration
			(minutes)		(minutes)
Bell, Lauren E.	LEB	7	355	0	0
Breese, Justin W.	JWB	0	0	4	218
Donnellan, Michael D.	MDD	6	272	0	0
Hebert, Kyle P.	KPH	5	229	0	0
Meucci, Jeffrey R.	JRM	7	385	0	0
Pryor, Garold “Flip” V.	FVP	7	399	0	0
Smith, Quinn T.	QTS	6	330	0	0
St. John, Carl	CSJ	0	0	5	317
White, Taylor D.	TDW	0	0	9	535

Table 3.–Summary of length frequency sample sizes for each method, by length type (measured vs. estimated) and behavior type (exposed vs. cryptic). The behavior observations were not a mandatory component of timed swim or transect sampling at Meares Pass, so estimate of “% Cryptic” provided for timed swims should be interpreted with caution because of small sample size (N.C. = Not Calculated).

Method	Metric	Gravina Island	Meares Pass
Timed Swim	# Sites	9	9
	Total # Lengths	663	137
	% Lengths Estimated	4	12
	# Behavior Observations	658	43
	% Cryptic	11	58
Transect	# Sites	15	10
	Total # Lengths	456	125
	% Lengths Estimated	15	41
	# Behavior Observations	456	8
	% Cryptic	24	N.C.

Table 4.–Summary of tests for differences in length frequency distributions between study areas and methods. Length frequency data were aggregated into 5 mm bin sizes and a subset of pairwise comparisons were tested using Kolmogorov-Smirnov two-sample tests. Tests were performed with a global $\alpha = 0.05$ and each test was adjusted for experiment-wise error rate using the Bonferroni correction factor ($\alpha = 0.008$).

Test	n	D-statistic	Critical D-value	p-value	Sig.
Gravina vs Meares (Timed Swim)	663; 137	0.274	0.153	5.2E-08	Yes
Gravina vs Meares (Transect)	456; 125	0.188	0.165	2.0E-03	Yes
Timed Swim vs. Transect (Gravina)	663; 226	0.149	0.104	9.9E-04	Yes
Timed Swim vs. Transect (Meares)	137; 111	0.120	0.208	3.2E-01	No

Table 5.–Results of regression analysis for individual abalone length vs. tide-corrected depth of observation, using timed swim dataset (Gravina Island and Meares Pass combined). The replicate was an individual observation for which abalone length and depth were both recorded.

Regression						
Multiple R	0.068					
R^2	0.005					
Adjusted R^2	0.003					
Std. Error	23.316					
n	800					
ANOVA	df	SS	MS	F	p-value	
Regression	1	1998	1998	3.68	0.06	
Residual	798	433806	544			
Total	799	435803				
	Coefficient	SE	t-value	p-value	-95%	+ 95%
Intercept	50.26	1.83	27.49	0.00	46.67	53.85
Slope	-0.30	0.16	-1.92	0.06	-0.61	0.01

Table 6.—Results of regression analysis for individual abalone length vs. tide-corrected depth of observation, using transect dataset (Gravina Island and Meares Pass combined). The replicate was an individual observation for which abalone length and depth were both recorded.

Regression						
Multiple R	0.02					
R^2	0.00					
Adjusted R^2	0.00					
Std. Error	21.14					
n	581					
ANOVA	df	SS	MS	F	p -value	
Regression	1	105	105	0.23	0.63	
Residual	579	258804	447			
Total	580	258908				
	Coefficient	SE	t -value	p -value	-95%	+ 95%
Intercept	48.03	1.70	28.26	0.00	44.69	51.37
Depth (ft, MLLW)	0.06	0.11	0.48	0.63	-0.17	0.28

Table 7.—Summary of tests for differences in length frequency distributions between historical and 2016 timed swim data for Meares Pass. Data from historical surveys were only included for sites also visited during 2016, but not all of these sites were sampled in 1986. Length frequency data were aggregated into 5 mm bin sizes and pairwise comparisons were tested using Kolmogorov-Smirnov two-sample tests. Tests were performed with a global $\alpha = 0.05$ and each test was adjusted for experiment-wise error rate using the Bonferroni correction factor ($\alpha = 0.017$).

Test	n	<i>D</i> -statistic	Critical <i>D</i> -value	<i>p</i> -value	Significant
1980–81 vs 1986	1,142; 986	0.235	0.067	5.1E-09	Yes
1980–81 vs 2016	1,142; 137	0.456	0.138	4.3E-10	Yes
1986 vs 2016	986; 137	0.649	0.139	1.1E-05	Yes

Table 8.—Results of comparisons of relative density between study areas for juvenile, adult, and all size classes combined (H_A : Gravina Island > Meares Pass). The comparison for each size class was tested using both a one-tailed two-sample Mann-Whitney U test for independent samples and a Mann-Whitney Exact test. Tests were performed with a global $\alpha = 0.05$ and each test was adjusted for experiment-wise error rate using the Bonferroni correction factor ($\alpha = 0.017$).

	Juveniles (< 50 mm)		Adults ($\geq$ 50 mm)		All Sizes Combined	
	Gravina Island	Meares Pass	Gravina Island	Meares Pass	Gravina Island	Meares Pass
n (# Sites)	9	9	9	9	9	9
Median (#/minute)	0.97	0.23	0.97	0.10	1.87	0.33
Rank Sum	109.5	61.5	118.5	52.5	120	51
U -value	16.5	64.5	7.5	73.5	6	75
mean U	40.5		40.5		40.5	
Standard Deviation	11.30		11.27		11.31	
z-score	2.12		2.93		3.05	
r (Effect Size)	0.50		0.69		0.72	
U -critical value	21.91		21.96		21.89	
Test type	Normal	Exact	Normal	Exact	Normal	Exact
p -value	0.017	0.020	0.002	0.001	0.001	0.001
Significant ($\alpha = 0.05$)	Yes	Yes	Yes	Yes	Yes	Yes
Significant ($\alpha = 0.017$)	Yes	No	Yes	Yes	Yes	Yes

Table 9.—Summary of test for difference in median relative density (all abalone sizes combined) between 2016 and 1980–1981 surveys in the Meares Pass study area. Comparison was performed using a one-tailed Wilcoxon Signed-Rank Exact Test for Paired Samples (H_A : 1980–1981 > 2016; $\alpha = 0.05$); the unit of replication was a dive site that was surveyed during both years (surveys in 1980 and 1981 were combined into one year for purposes of this comparison).

	1980–81	2016
# of Observations	9	9
Mean (#/minute)	6.65	0.51
Standard Deviation	3.67	0.48
Median (#/minute)	7.95	0.33
T^+	0	
T^-	45	
T	0	
Mean	22.50	
Standard Deviation	8.44	
z-score	2.61	
Effect Size r	0.61	
p -value	2.0E-03	
Significant	Yes	

Table 10.—Results of comparisons of abalone absolute density between study areas for juvenile, adult, and all size classes combined (H_A : Gravina Island > Meares Pass). The comparison for each size class was tested using both a one-tailed two-sample Mann-Whitney U test for independent samples and a Mann-Whitney Exact test. To assess statistical significance, the alpha value was adjusted using a Bonferroni correction to account for inflation of experiment-wise error rate associated with multiple tests.

	Juveniles (< 50 mm)		Adults ($\geq$ 50 mm)		All Sizes Combined	
	Gravina Island	Meares Pass	Gravina Island	Meares Pass	Gravina Island	Meares Pass
# of replicates (Sites)	15	9	15	9	15	9
Median (#/m ²)	0.35	0.28	0.20	0.19	0.70	0.44
Rank Sum	202.5	97.5	203	97	211	89
U -value	52.5	82.5	52	83	44	91
mean U	67.5		67.5		67.5	
Standard Deviation	16.75		16.70		16.76	
z-score	0.90		0.93		1.40	
r (Effect Size)	0.18		0.19		0.29	
U -critical value	39.95		40.03		39.93	
Test type	<u>Normal</u>	<u>Exact</u>	<u>Normal</u>	<u>Exact</u>	<u>Normal</u>	<u>Exact</u>
p -value	0.185	0.206	0.177	0.189	0.080	0.087
Significant ($\alpha = 0.05$)	No	No	No	No	No	No
Adjusted Significance ($\alpha = 0.017$)	No	No	No	No	No	No

Table 11.—Results of one-tailed, one-sample Wilcoxon Signed-Ranks Tests of the alternative hypothesis that the site-specific median density of adult (≥ 50 mm) abalone was significantly less than a hypothesized median density of $0.2/\text{m}^2$. The hypothesized median density used here was substituted for the mean density threshold density for recruitment failure estimated by Babcock and Keesing (1999) and used as a Minimum Viable Population density for red abalone in California's Abalone Recovery and Monitoring Plan (CDFW 2005). The sample size (n) is the total number of $1 \times 4 \text{ m}^2$ quadrats sampled along a transect. To reduce the probability of false negative results, each test was set to $\alpha = 0.05$ and not adjusted for experiment-wise error rate. *Note the test was significant for the Gravina Island site 101-29 #004 in the positive direction.

Study Area	Site	n	Mean ($\#/\text{m}^2$)	Median ($\#/\text{m}^2$)	Effect Size (r)	T -value	T -crit	p -value	Signif. (Exact)
Gravina Island	101-25 #026	10	0.33	0.25	0.41	15	11	0.12	No
	101-27 #009	10	0.10	0.00	0.49	13	12	0.08	No
	#010	10	0.25	0.00	0.18	22	12	0.31	No
	#013	10	0.05	0.00	0.84	3	12	0.00	Yes
	#014	10	0.13	0.00	0.56	11	12	0.05	No
	#015	10	0.55	0.25	0.54	11	11	0.05	No
	#016	8	0.47	0.13	0.20	14	6	0.32	No
	#024	10	0.13	0.13	0.41	15	12	0.12	No
	101-29 #001	10	0.23	0.00	0.18	22	12	0.31	No
	#002	10	0.35	0.25	0.31	18	11	0.19	No
	#003	10	0.10	0.00	0.49	13	12	0.08	No
	#004	10	1.23	1.13	0.79	3	11	0.00	Yes*
	#005	10	0.05	0.00	0.84	3	12	0.00	Yes
	#006	10	0.20	0.25	0.18	18	9	0.33	No
	#108	10	0.20	0.00	0.18	22	12	0.31	No
Meares Pass	104-30 #016	10	0.08	0.00	0.72	6	12	0.01	Yes
	#017	8	0.16	0.00	0.10	16	7	0.42	No
	#018	10	0.05	0.00	0.84	3	12	0.00	Yes
	#019	9	0.19	0.00	0.36	11	7	0.19	No
	#020	6	0.13	0.13	0.39	6	3	0.22	No
	#021	10	0.20	0.00	0.18	22	12	0.31	No
	#022	10	0.28	0.00	0.18	22	12	0.31	No
	#023	9	0.22	0.25	0.18	18	9	0.33	No
	#024	10	0.20	0.00	0.25	20	12	0.25	No
	#102	10	0.00	0.00	-	-	-	-	Yes

Table 12.—Results of density method comparison (timed swims vs. transect) using simple linear regression. Relative density (timed swims; y-variable) was regressed against absolute density (transects; x-variable). Sites were the replicate and data from both study areas were combined for analysis.

Regression						
Multiple R	0.44					
R^2	0.19					
Adjusted R^2	0.14					
Std. Error	0.39					
n	18					
ANOVA	df	SS	MS	F	p -value	
Regression	1	0.59	0.59	3.87	0.07	
Residual	16	2.42	0.15			
Total	17	3.01				
	Coefficient	SE	t -value	p -value	-95%	+ 95%
Intercept	0.31	0.13	2.35	0.03	0.03	0.59
Slope	0.13	0.06	1.97	0.07	-0.01	0.26

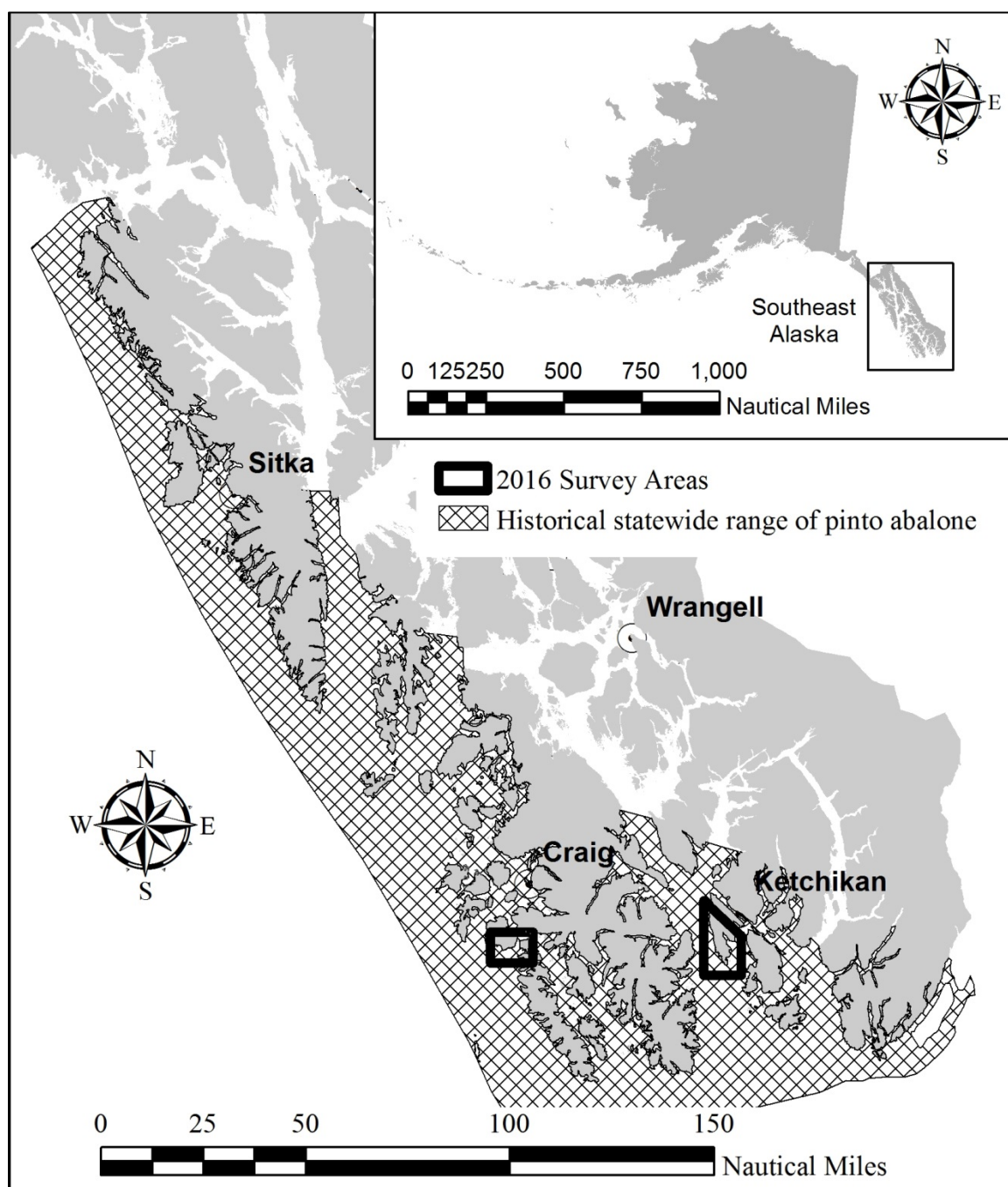


Figure 1.—Historical geographic range of pinto abalone in Southeast Alaska.

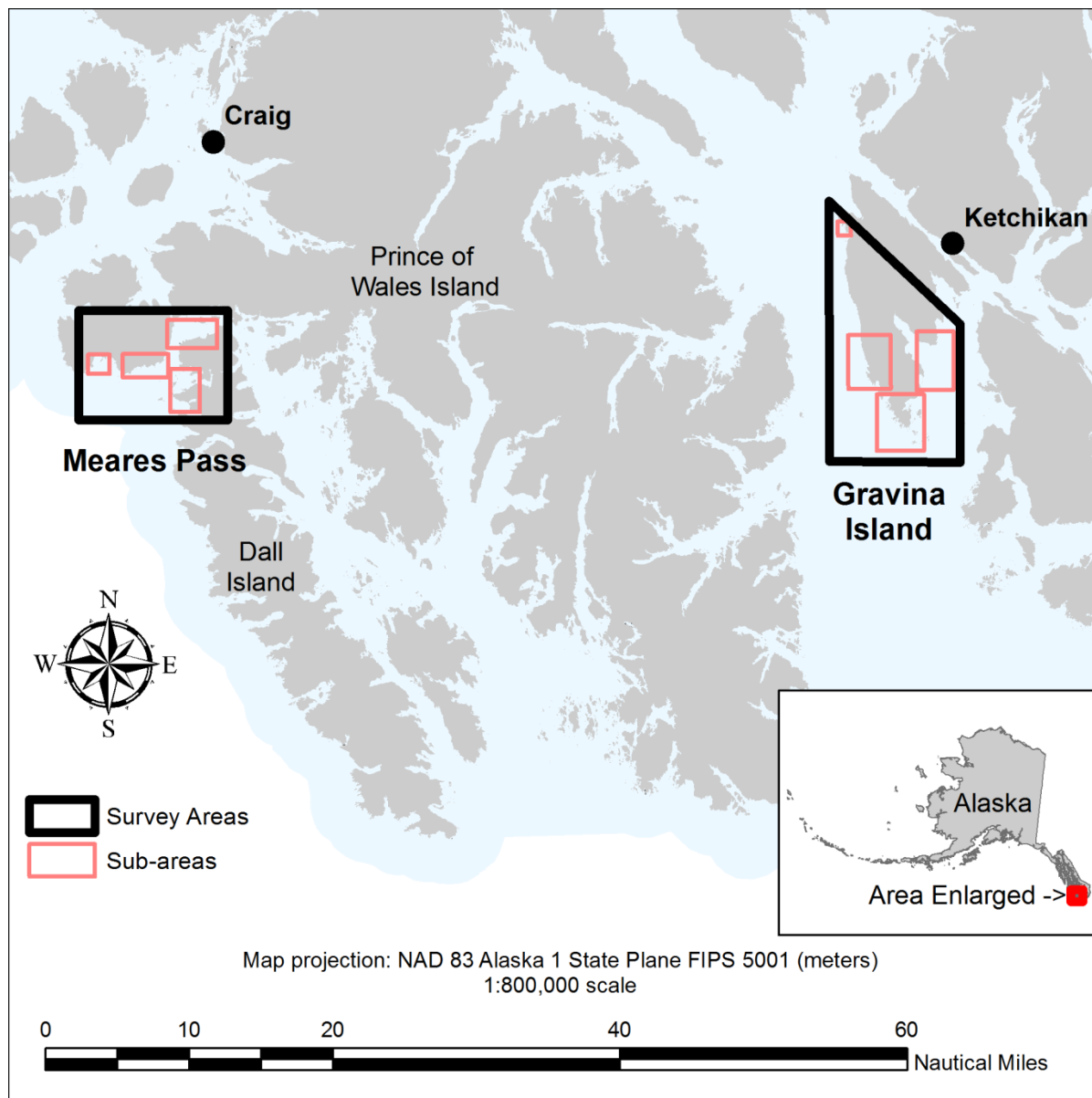


Figure 2.—Areas chosen for this study. Multiple subareas in each study area were designated and prioritized for surveying, if time allowed.

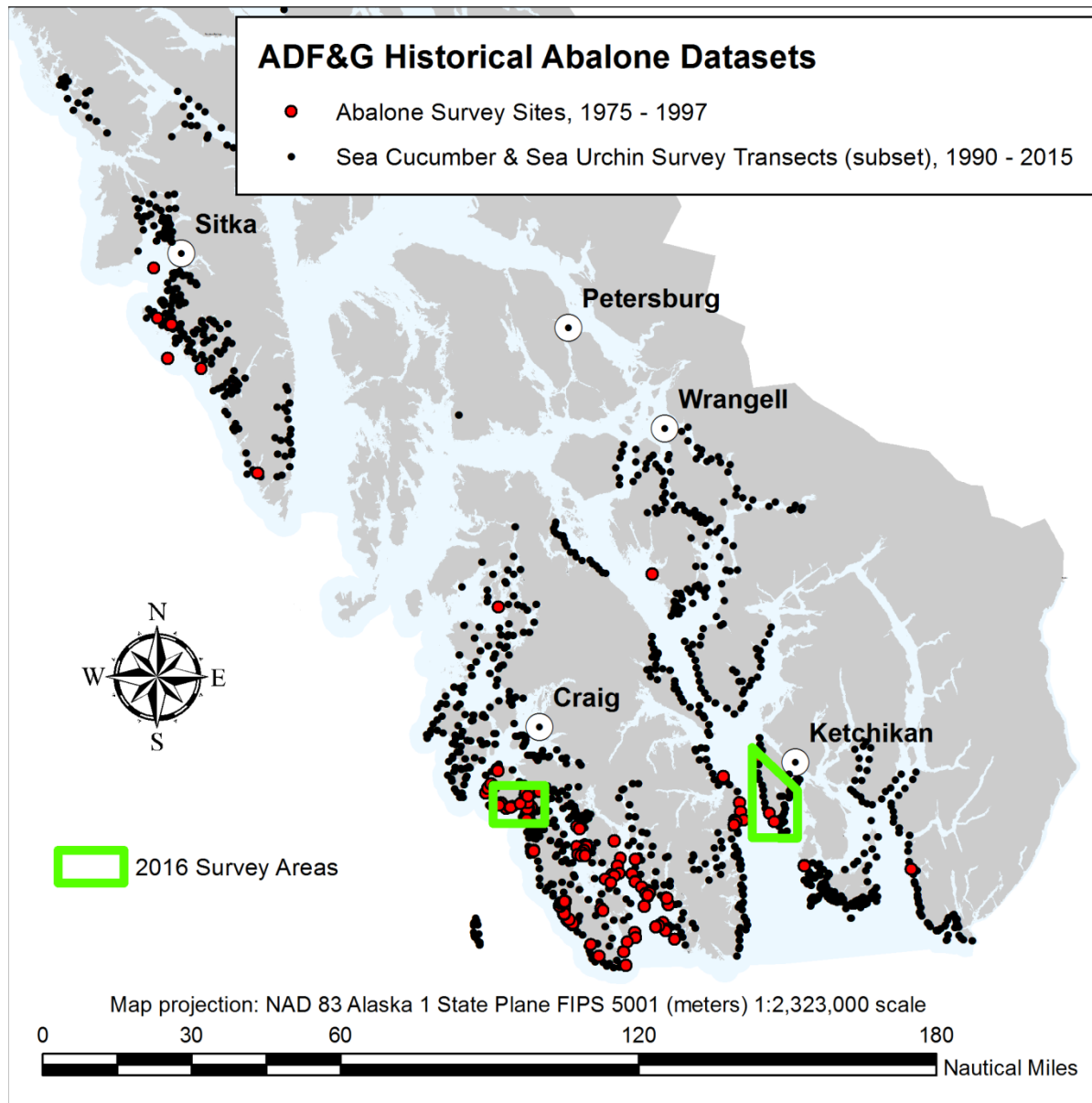


Figure 3.—Dedicated and non-targeted abalone surveys by ADF&G.

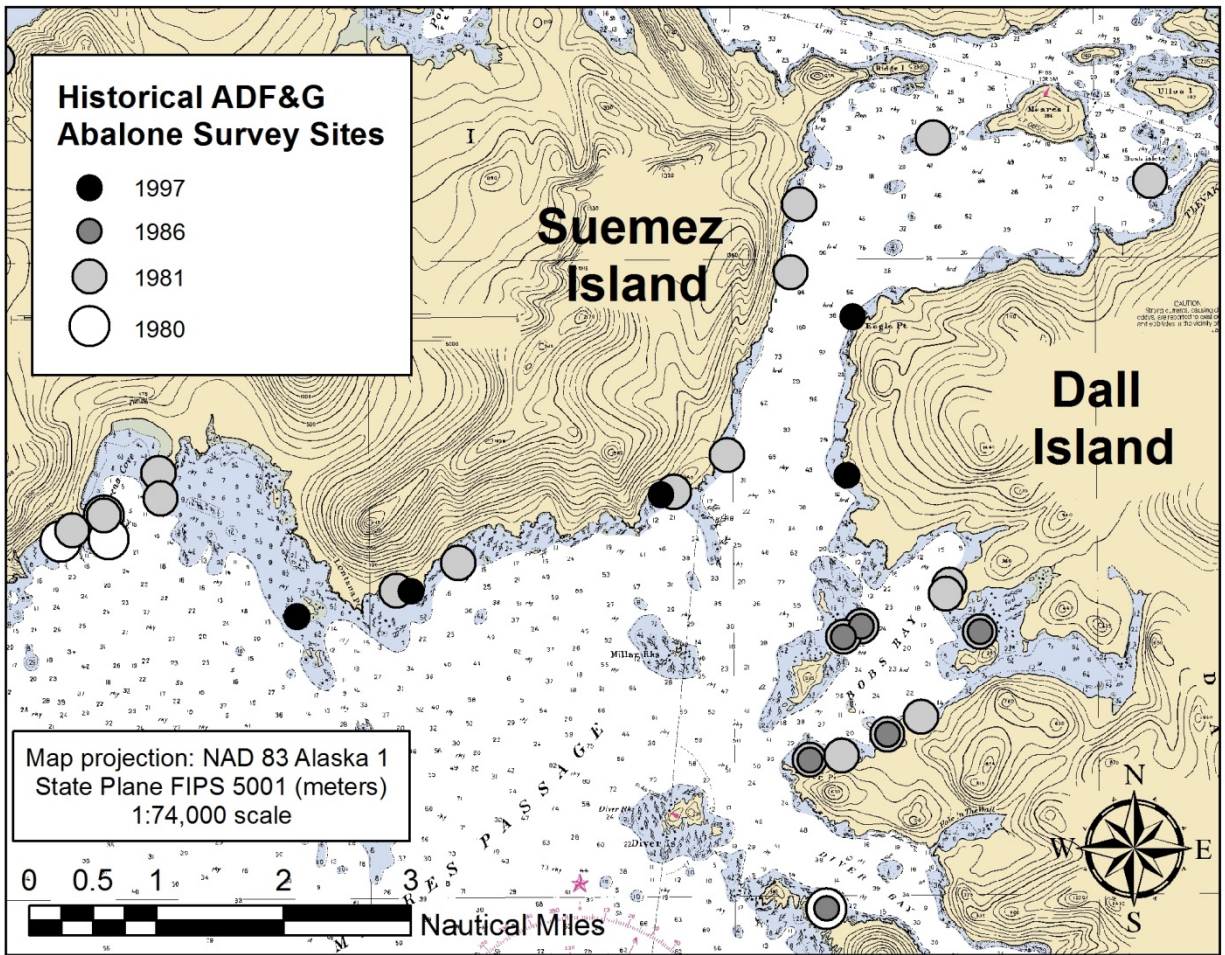


Figure 4.—Historical ADF&G abalone survey sites in the Meares Pass study area.

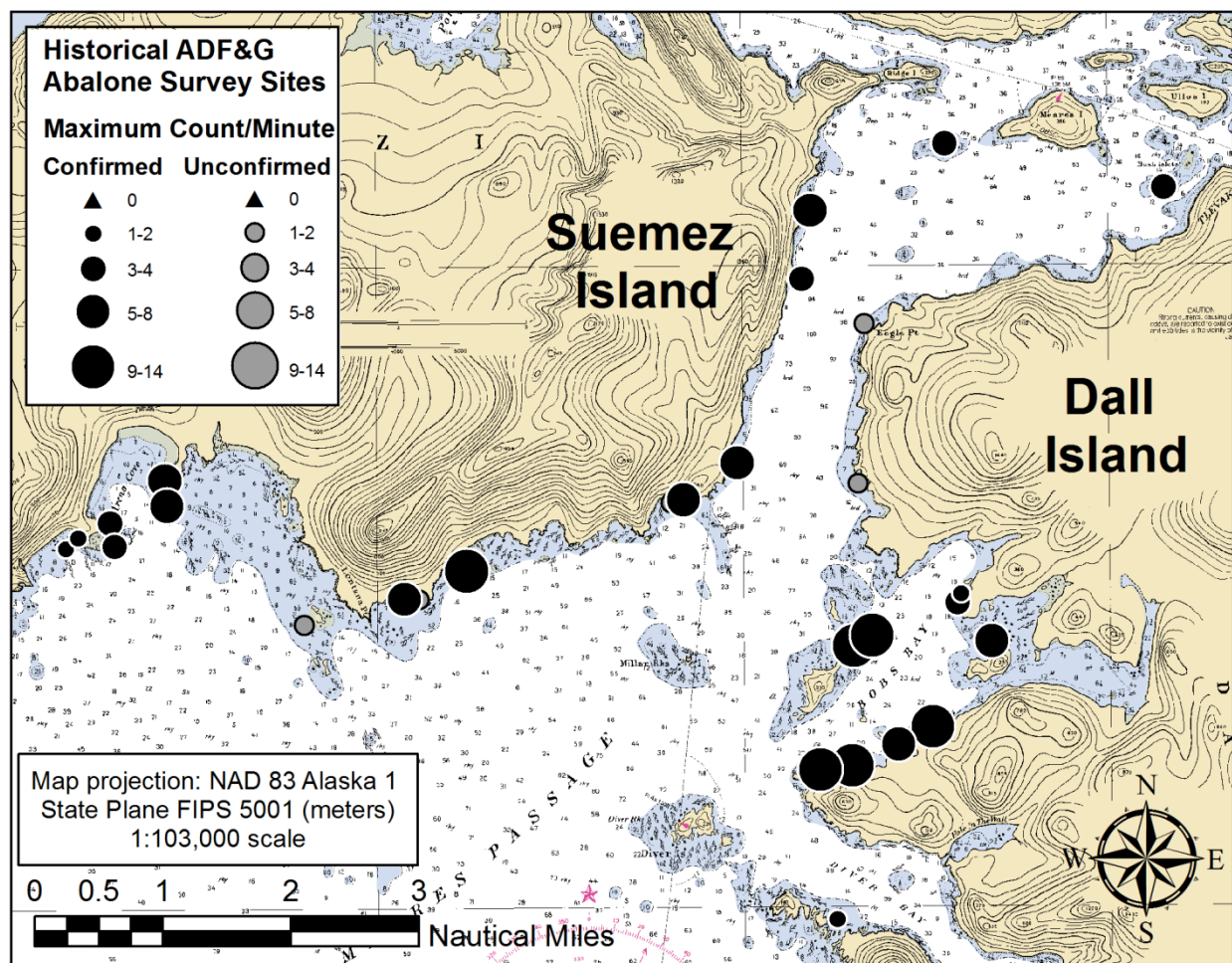


Figure 5.—Historical ADF&G abalone survey sites in the Meares Pass study area, symbolized according to abalone relative abundance. “Confirmed” counts per minute indicated dives in which the total dive time was recorded in the database, whereas dive times were estimated for “Unconfirmed” dives and were therefore of lower quality.

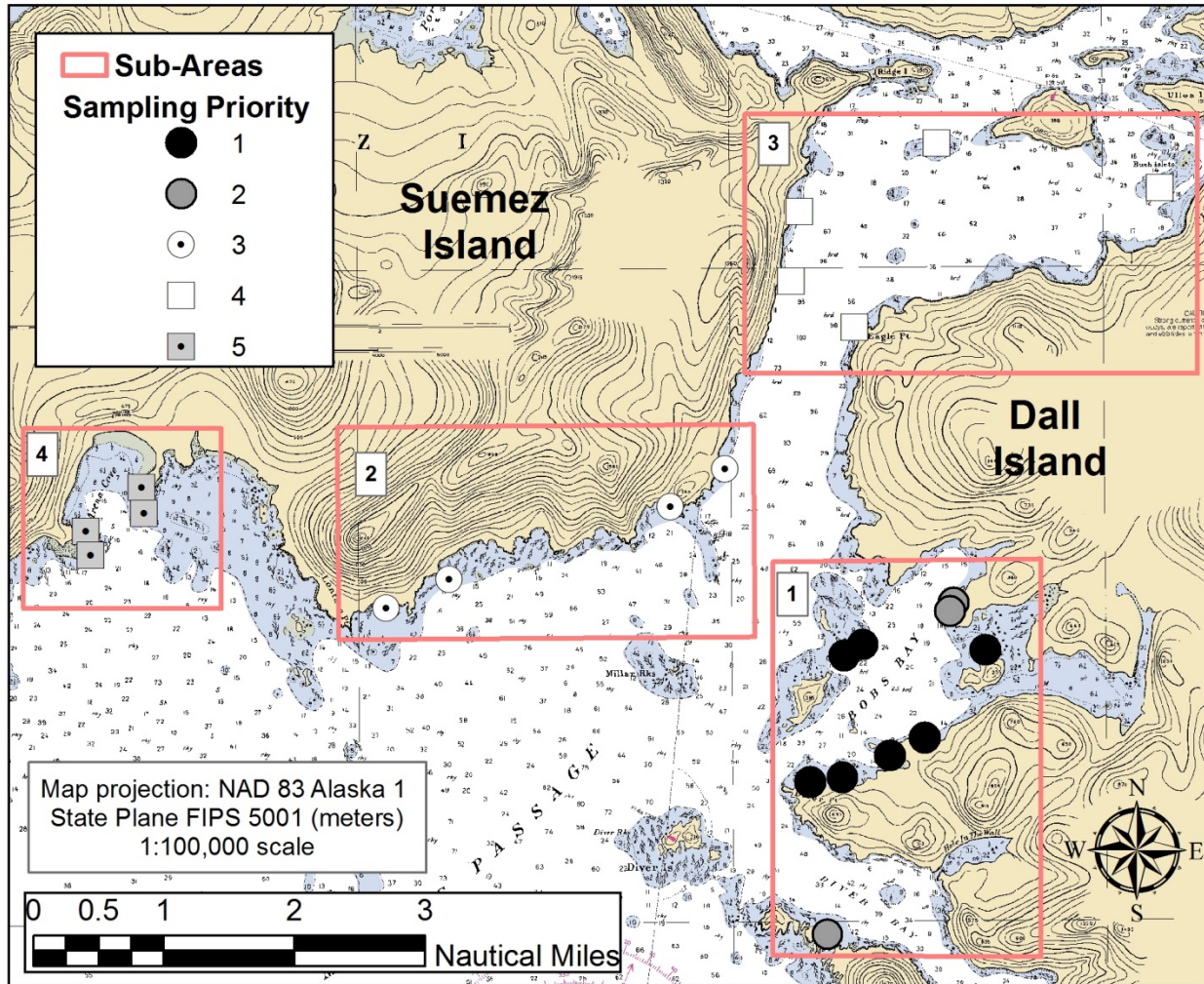


Figure 6.–Field chart for Meares Pass study area, with survey sites prioritized.

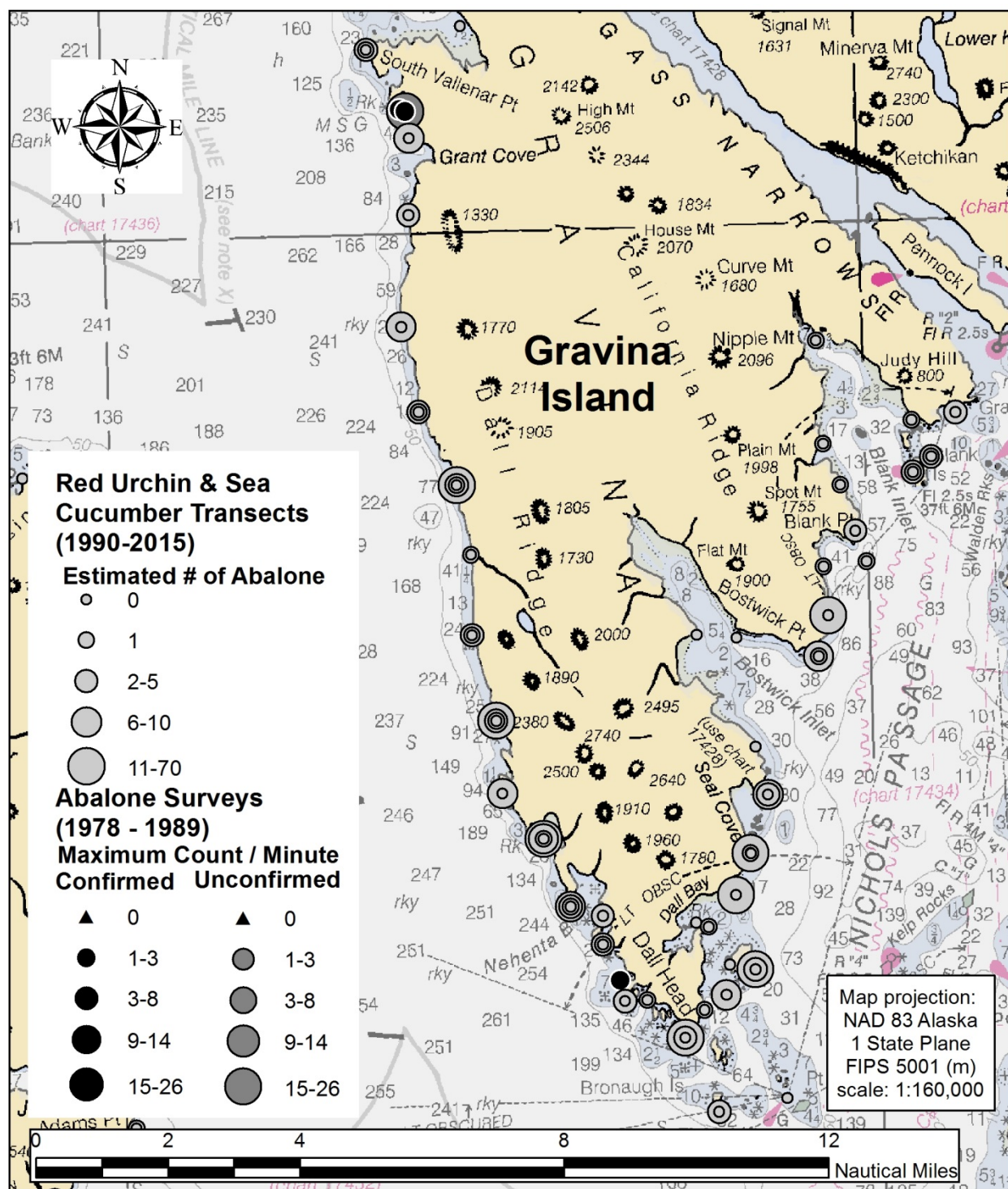


Figure 7.—Historical ADF&G abalone survey sites and sea cucumber and sea urchin survey sites in the Gravina Island study area. Graduated symbols indicate relative abundance. “Confirmed” counts per minute indicated dives in which the total dive time was recorded in the database, whereas dive times were estimated for “Unconfirmed” dives and were therefore of lower quality.

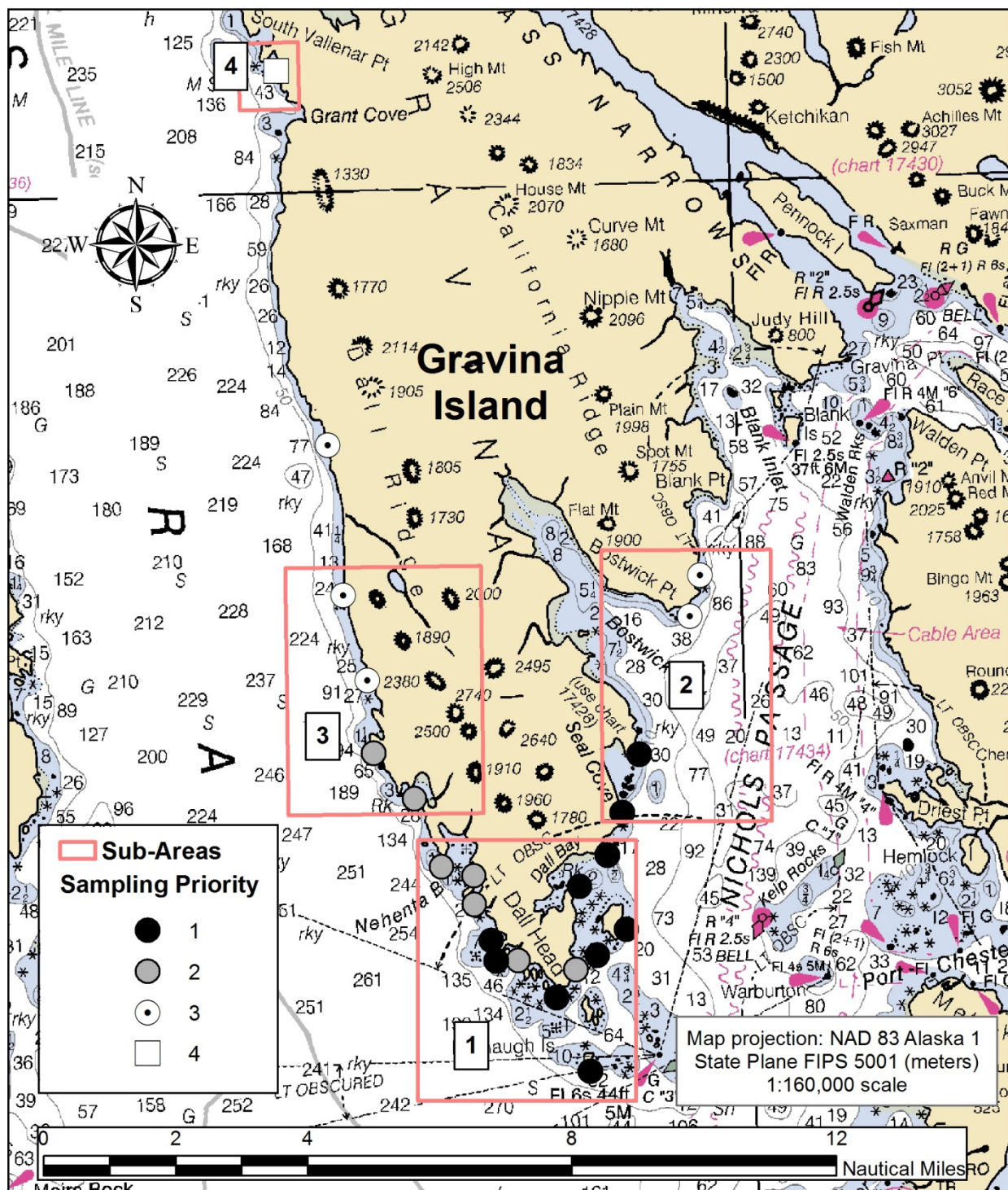


Figure 8.—Field chart for Gravina Island study area, with survey sites prioritized.

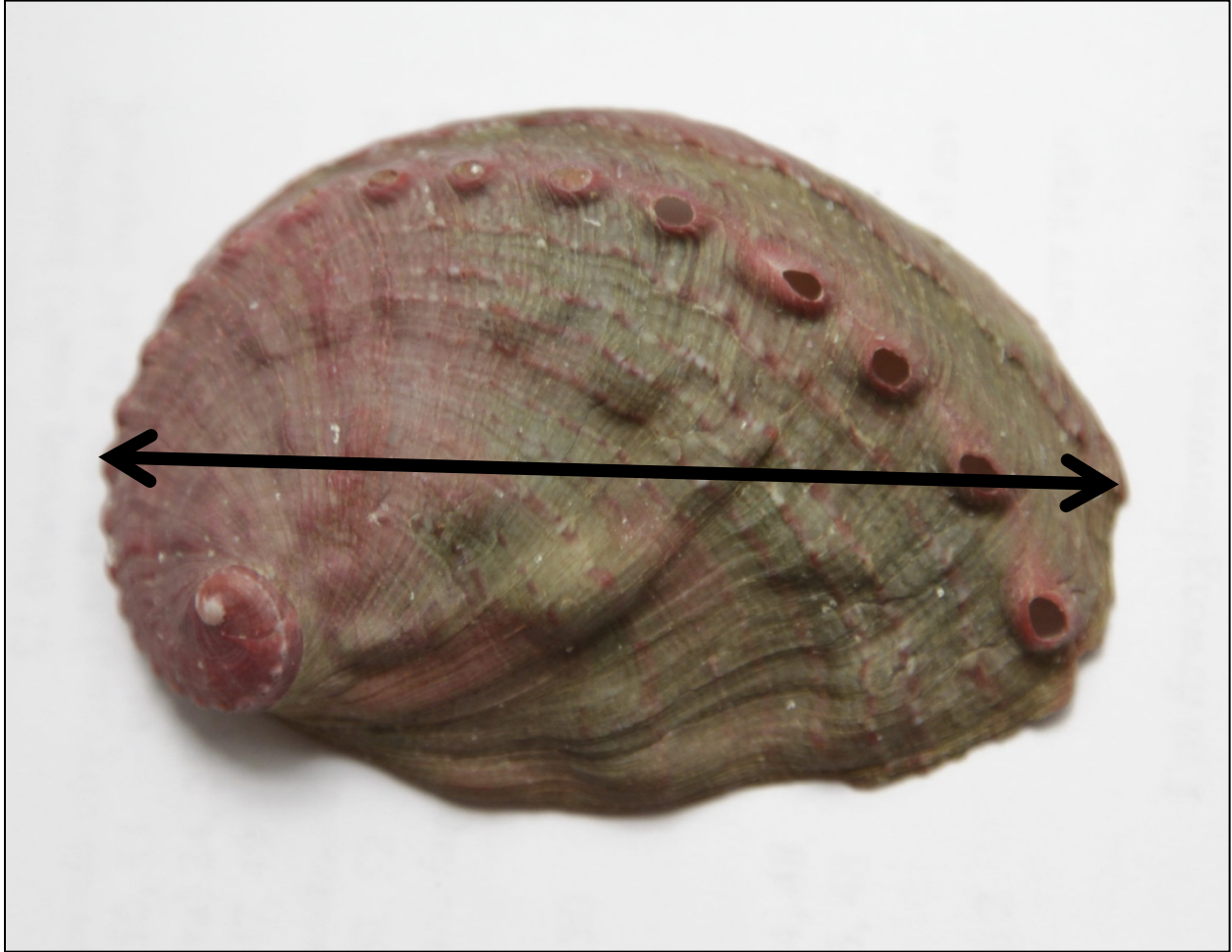


Figure 9.—Abalone shell with indicator line representing the axis of length measurement used in this study (across the maximum shell dimension, to the nearest mm).

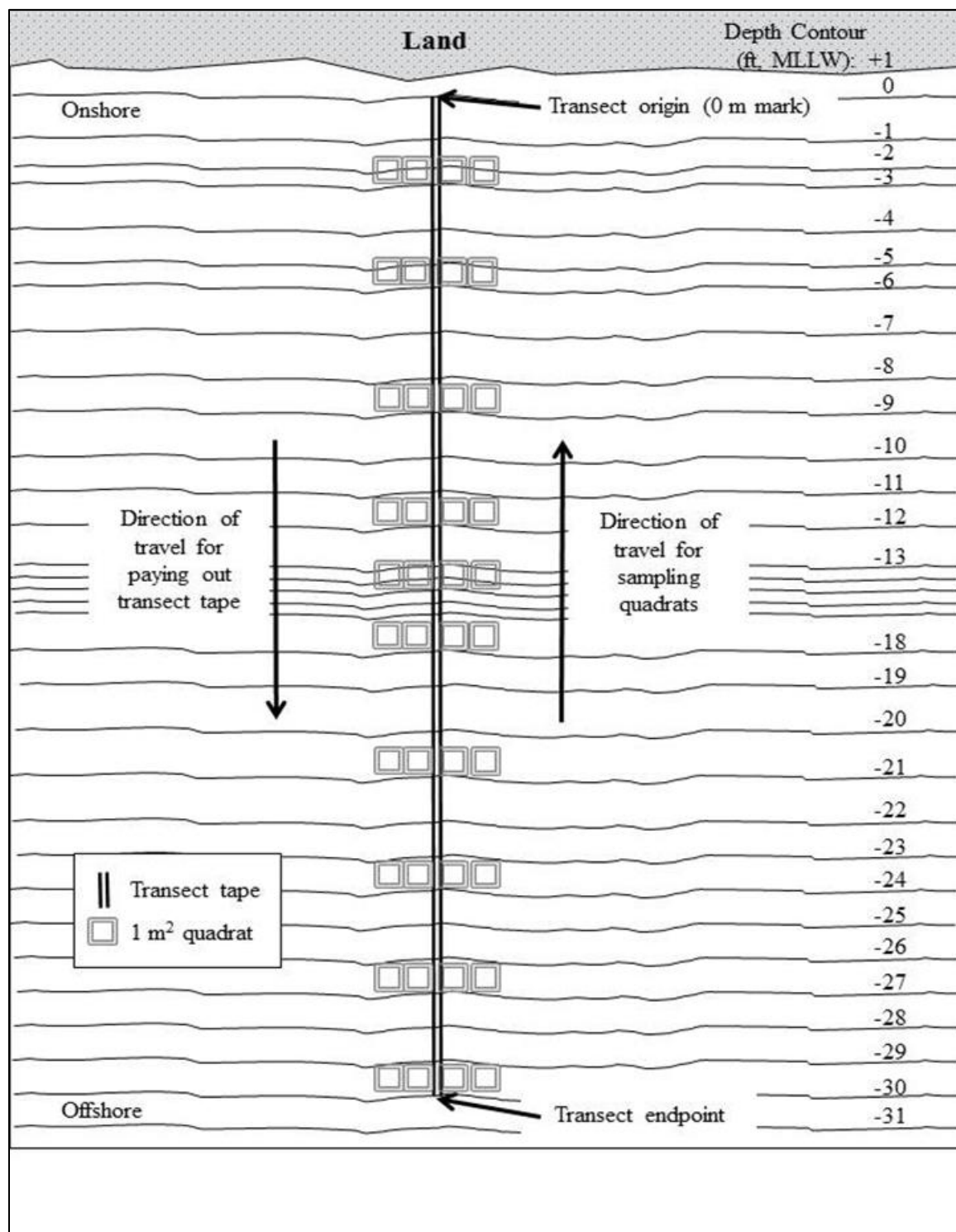


Figure 10.—Schematic of permanent site layout and orientation relative to shoreline.

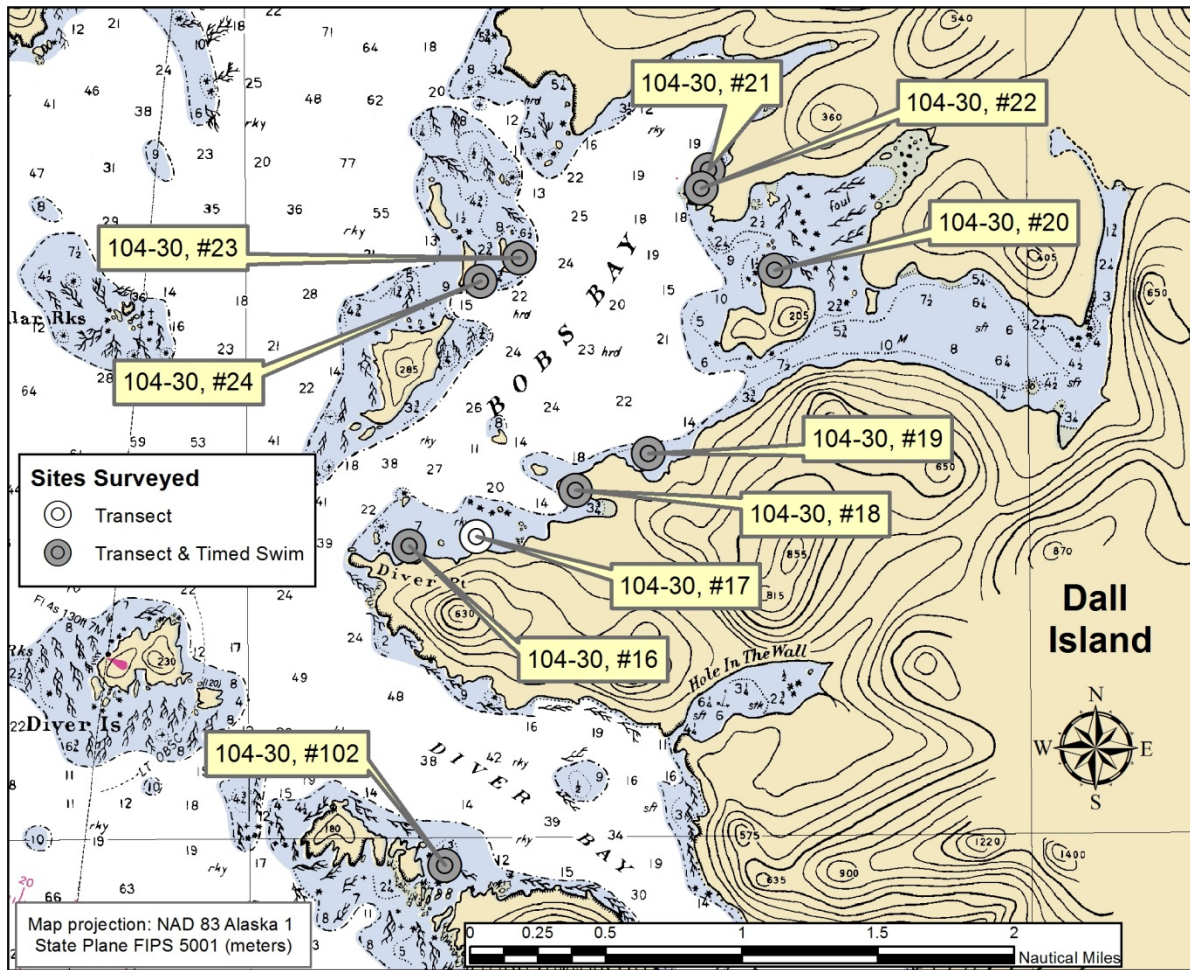
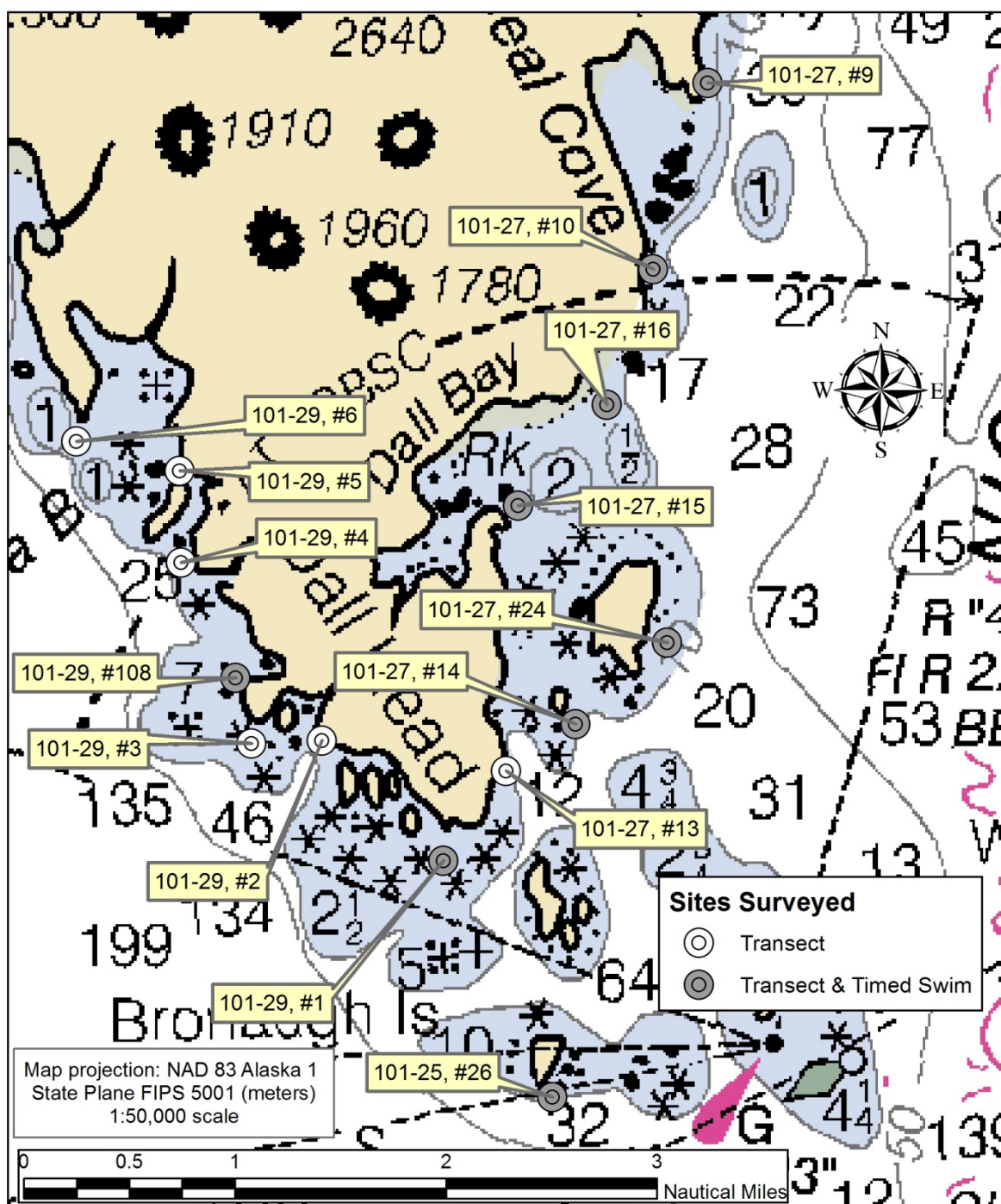


Figure 11.—Map of completed transects and timed swims in the Meares Pass study area.



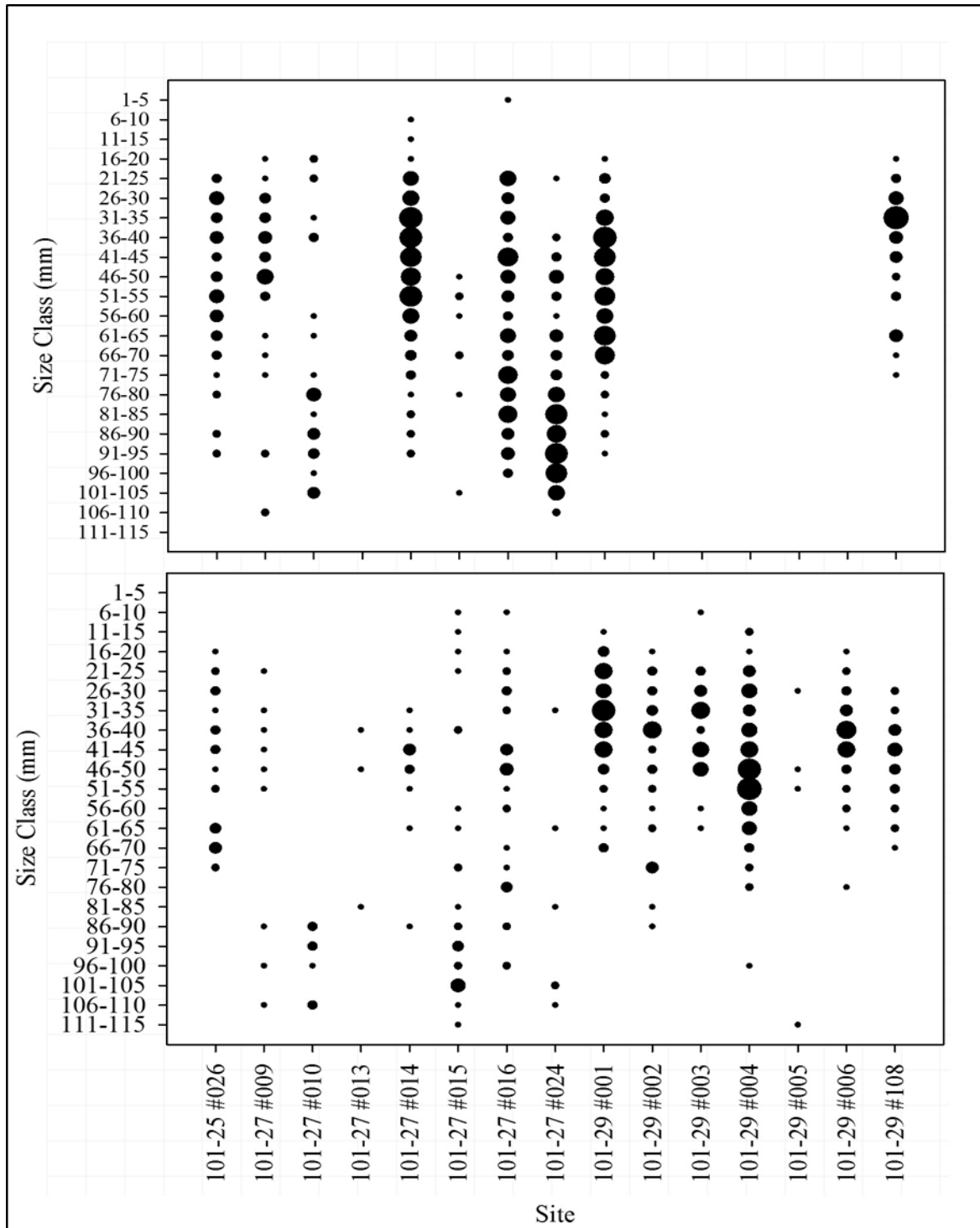


Figure 12.—Abalone size frequencies from Gravina Island study area sites, as recorded during timed swims (top graph) and transects (lower graph). The area of the filled circles are proportional to the count for a given size class, with the smallest circle equal to a count of one and the largest circle equal to a count of 21. Transect surveys were conducted at all 15 sites, but timed swims were done at only 10 sites, so 5 sites do not have size frequency data.

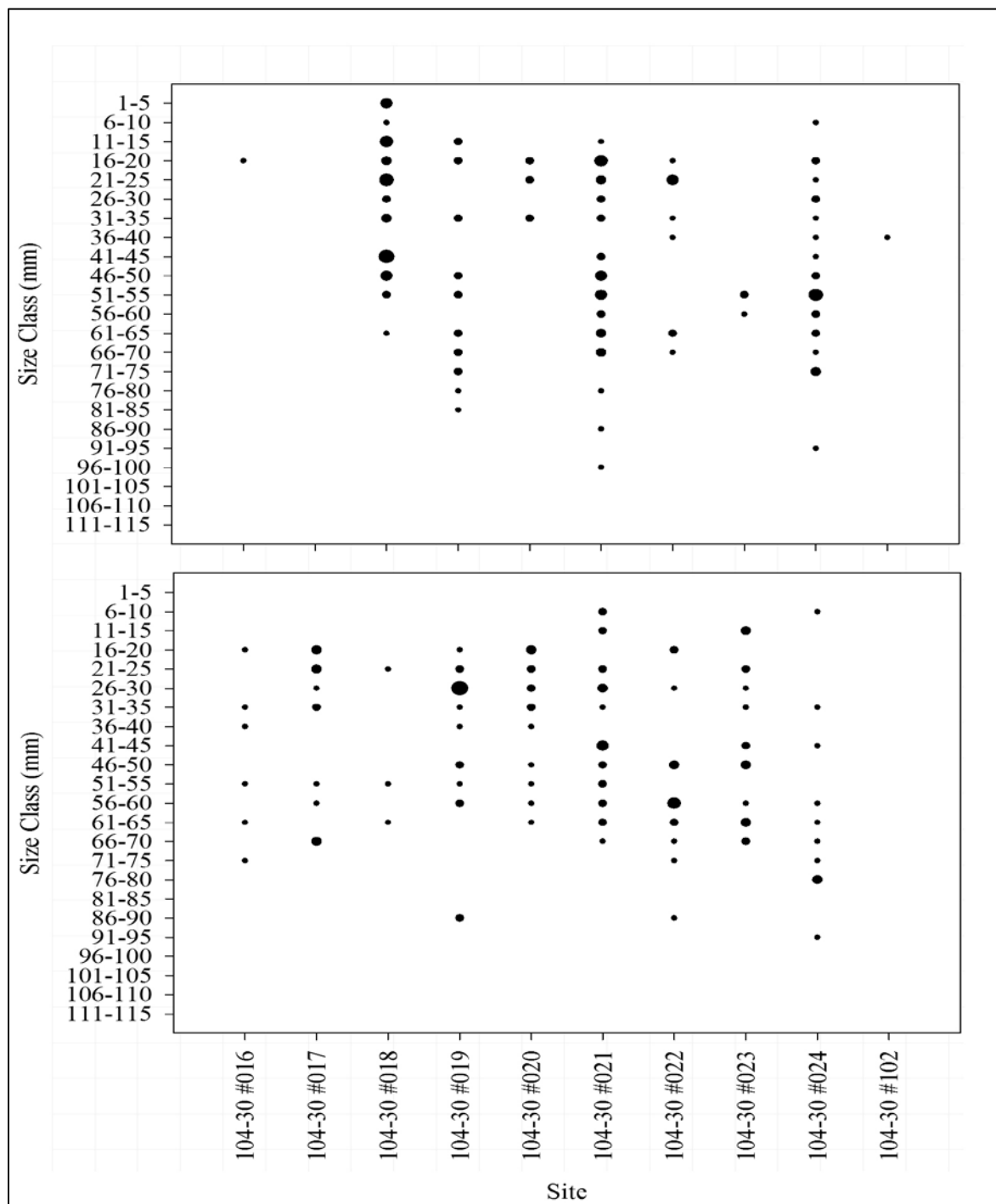


Figure 13.—Abalone size frequencies from Meares Pass study area sites, as recorded during timed swims (top graph) and transects (lower graph). The area of the filled circles are proportional to the count for a given size class, with the smallest circle equal to a count of one and the largest circle equal to a count of 7. Transect surveys were conducted at all 10 sites, and timed swims were done at all but one site (104-30 #017). No abalone were observed during the transect survey at site 104-30 #102.

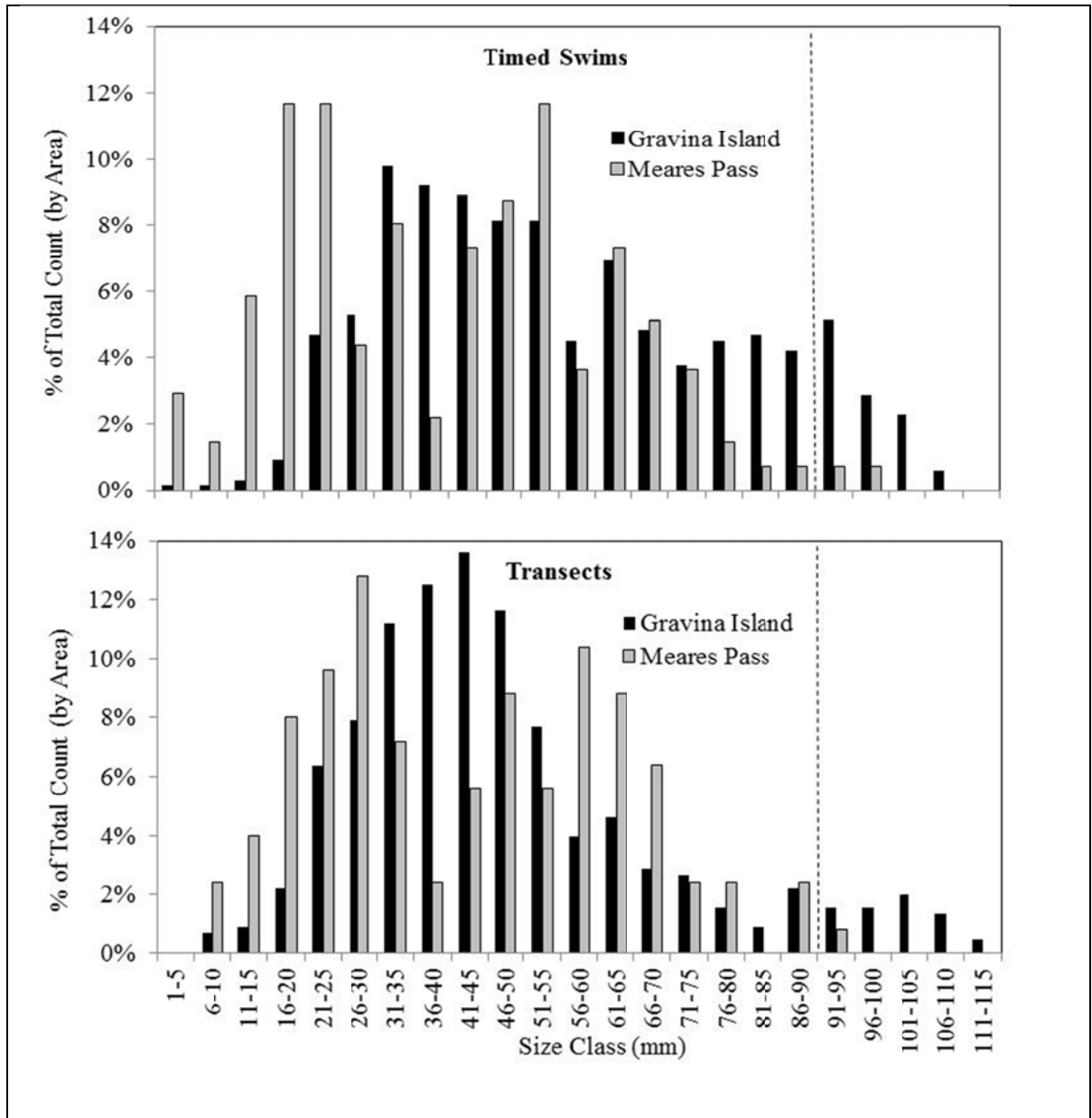


Figure 14.—Abalone length frequencies from timed swims and transects, standardized as a proportion of total count by method and study area. For reference, the vertical dashed line indicates the present legal size limit (89 mm) for subsistence and personal use fisheries.

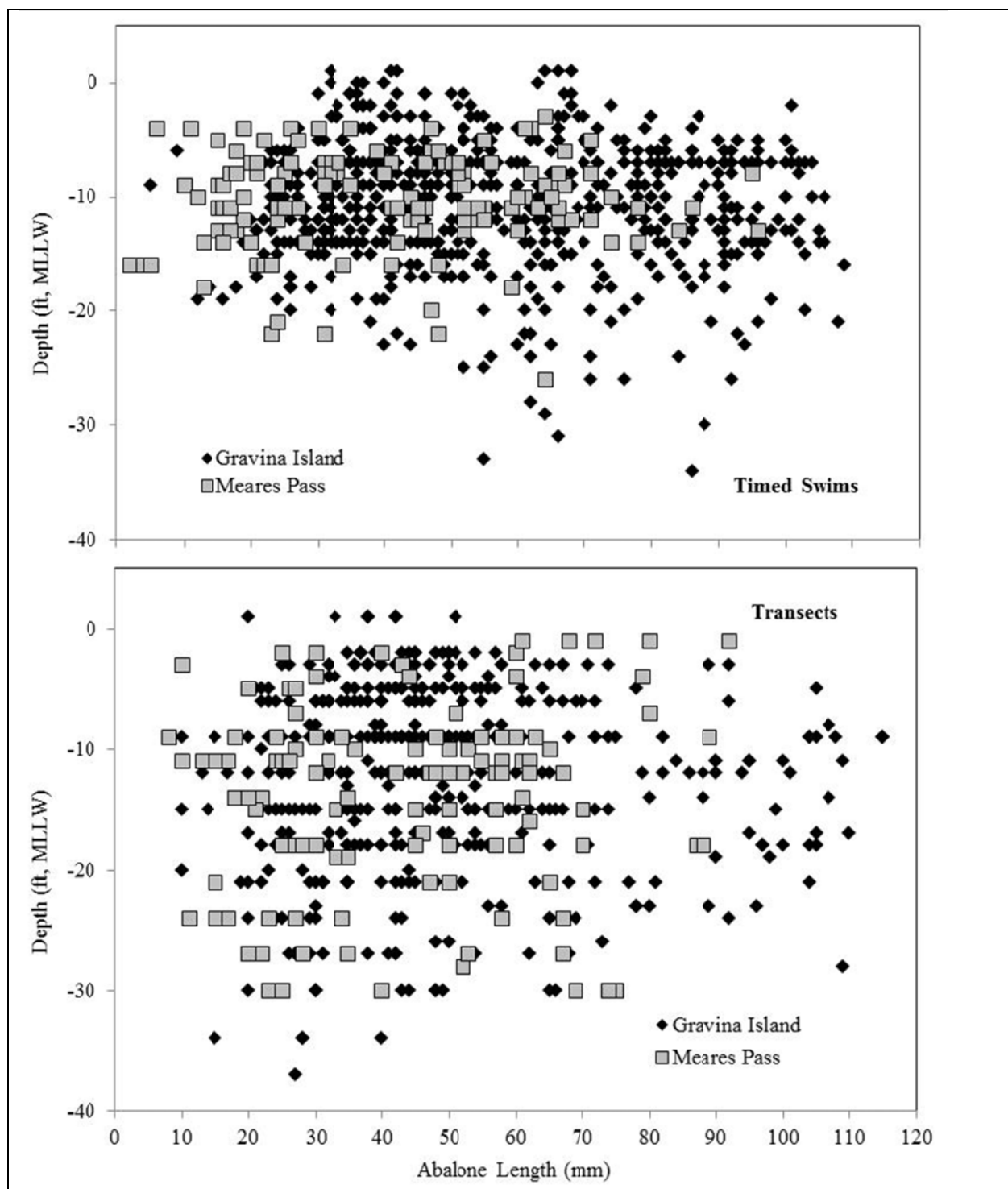


Figure 15.—Abalone length vs. tide-corrected depth of observation, by study area and method. The replicate was an individual observation for which abalone length and depth were both recorded.

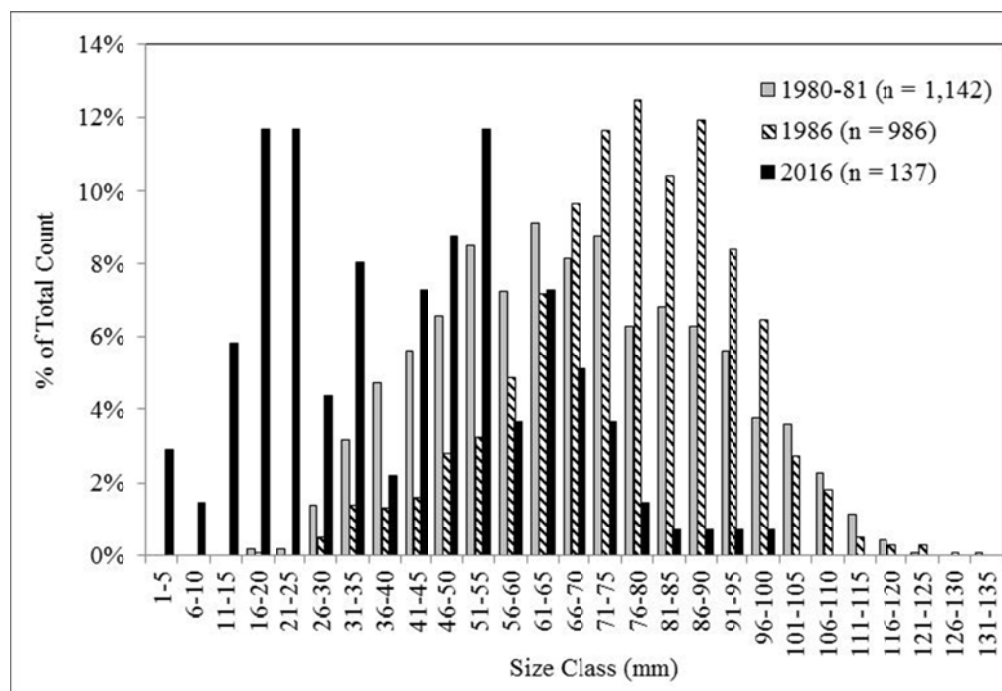


Figure 16.—Historical and extant abalone length frequencies in Meares Pass, collected during timed swims and standardized for each survey year(s) as a proportion of the total count for that year.

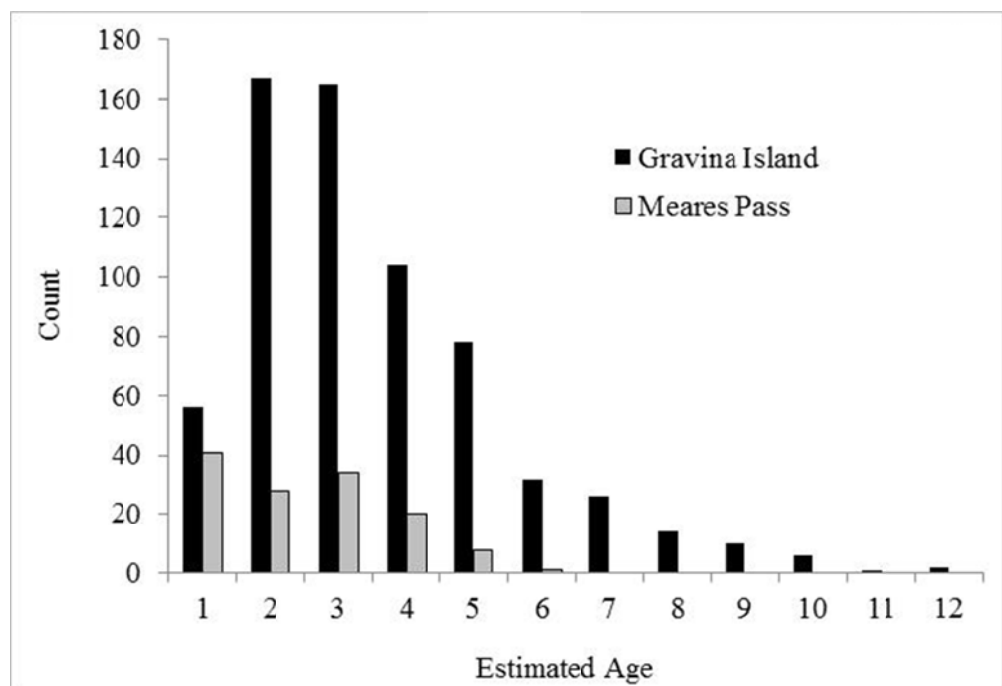


Figure 17.—Estimated ages of abalone in each study area, calculated using length frequency data collected during timed swims and age-length keys developed from a dataset collected by Woodby et al. (2000) and Shepherd et al. (2000).

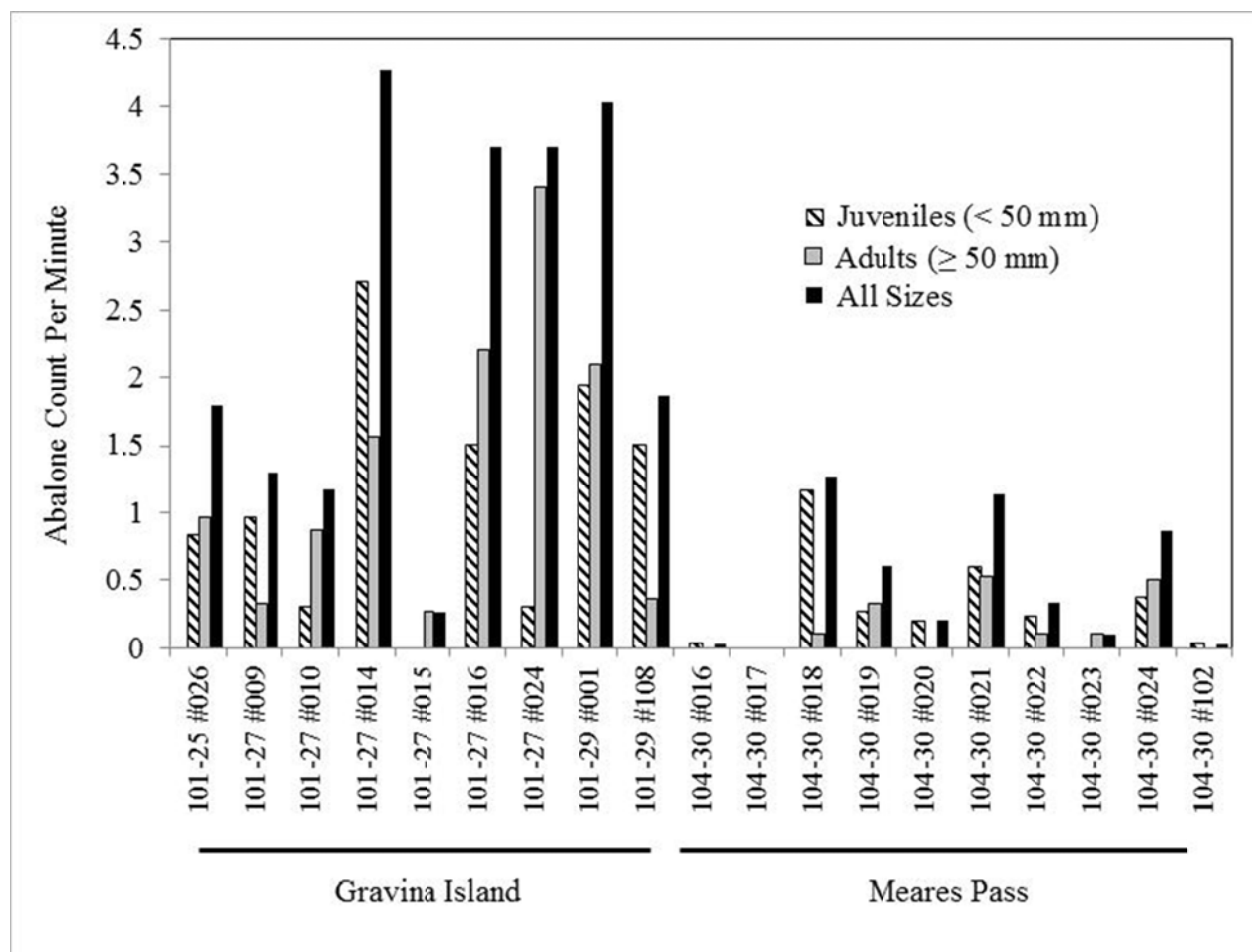


Figure 18.—Relative density of abalone observed during timed swims at each site within each study area. The timed swim at site 104-30 #17 in Meares Pass was aborted due to low visibility and should be considered “no data”. There was no estimate of variability associated with each value because only one timed swim was done per site.

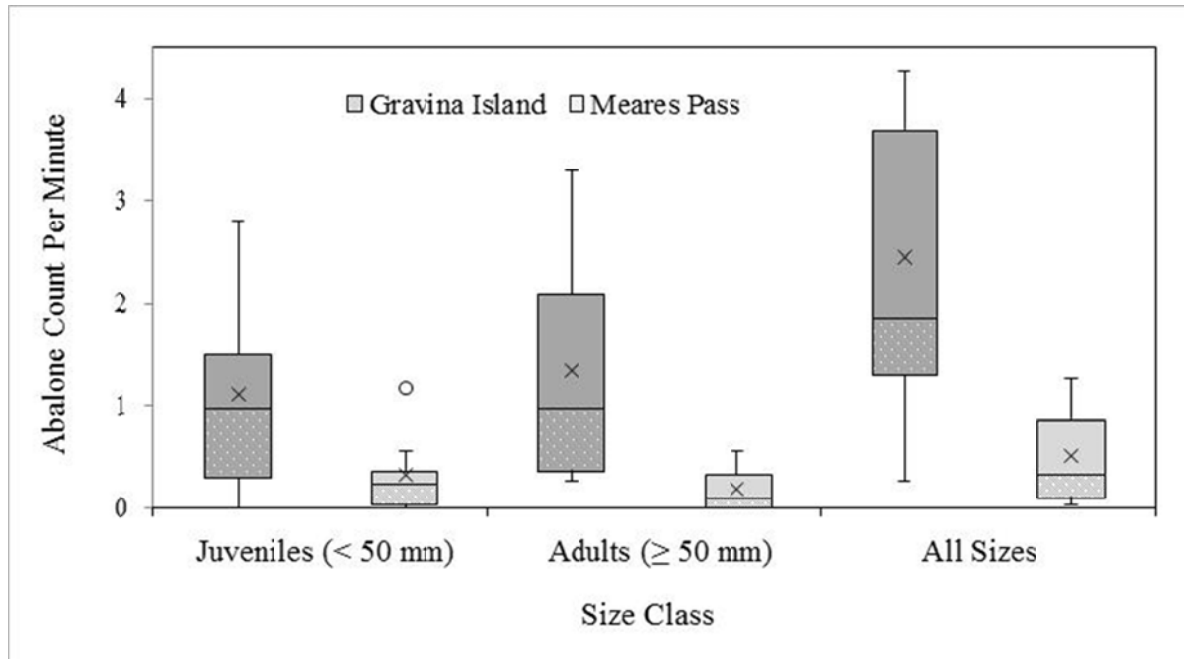


Figure 19.—Relative density of abalone by size class and study area (replicates = sites). Box and whisker plots of densities observed within 1x4 m² quadrats. The bottom (stippled pattern) and top of each box are the first and third quartiles, respectively, and the horizontal line inside the box is the second quartile (i.e., the median). The mean is indicated by an “x”, and the positive and negative whiskers extend to the maximum and minimum quadrat density values, respectively.

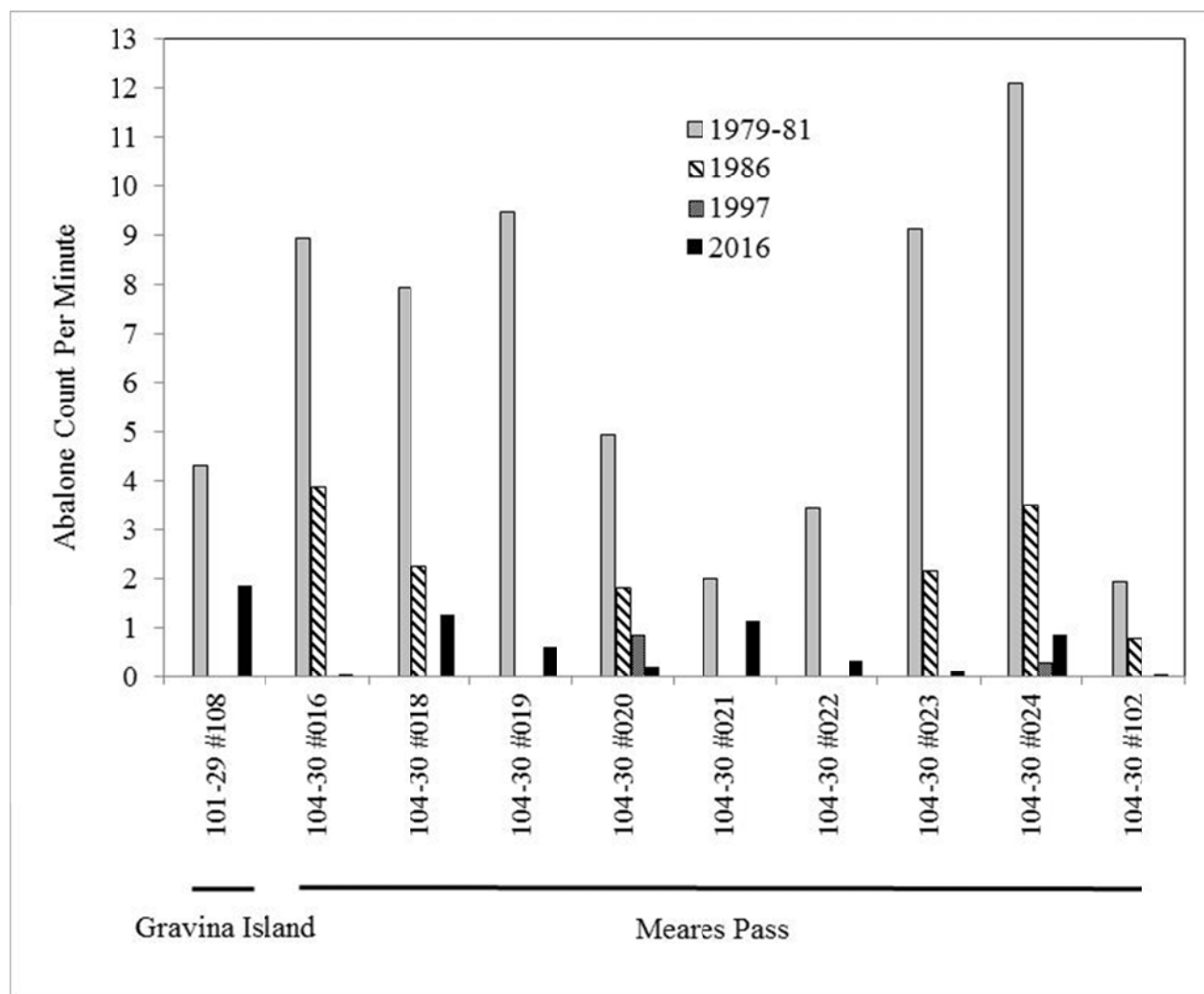


Figure 20.—Relative density of abalone (all sizes combined) by survey year for all sites surveyed using timed swims and for which historical data exists. Historical data compiled from Blankenbeckler and Larson (unpublished data), Woodby et. al. (2000), and Shepherd et al. (2000).

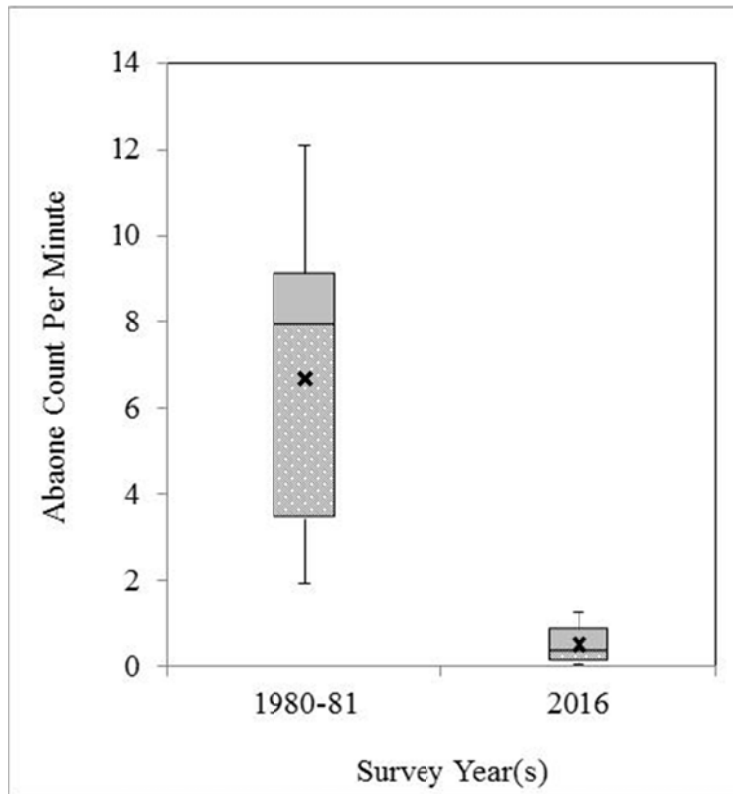


Figure 21.—Relative density of abalone (all sizes combined) summarized for all sites in common ($n = 9$) between survey years in the Meares Pass study area. Historical data compiled from Blankenbeckler and Larson (unpublished data), Woodby et al. (2000), and Shepherd et al. (2000). The bottom (stippled pattern) and top of each box are the first and third quartiles, respectively, and the horizontal line inside the box is the second quartile (i.e. the median). The mean is indicated by an “x”, and the positive and negative whiskers extend to the maximum and minimum quadrat density values, respectively.

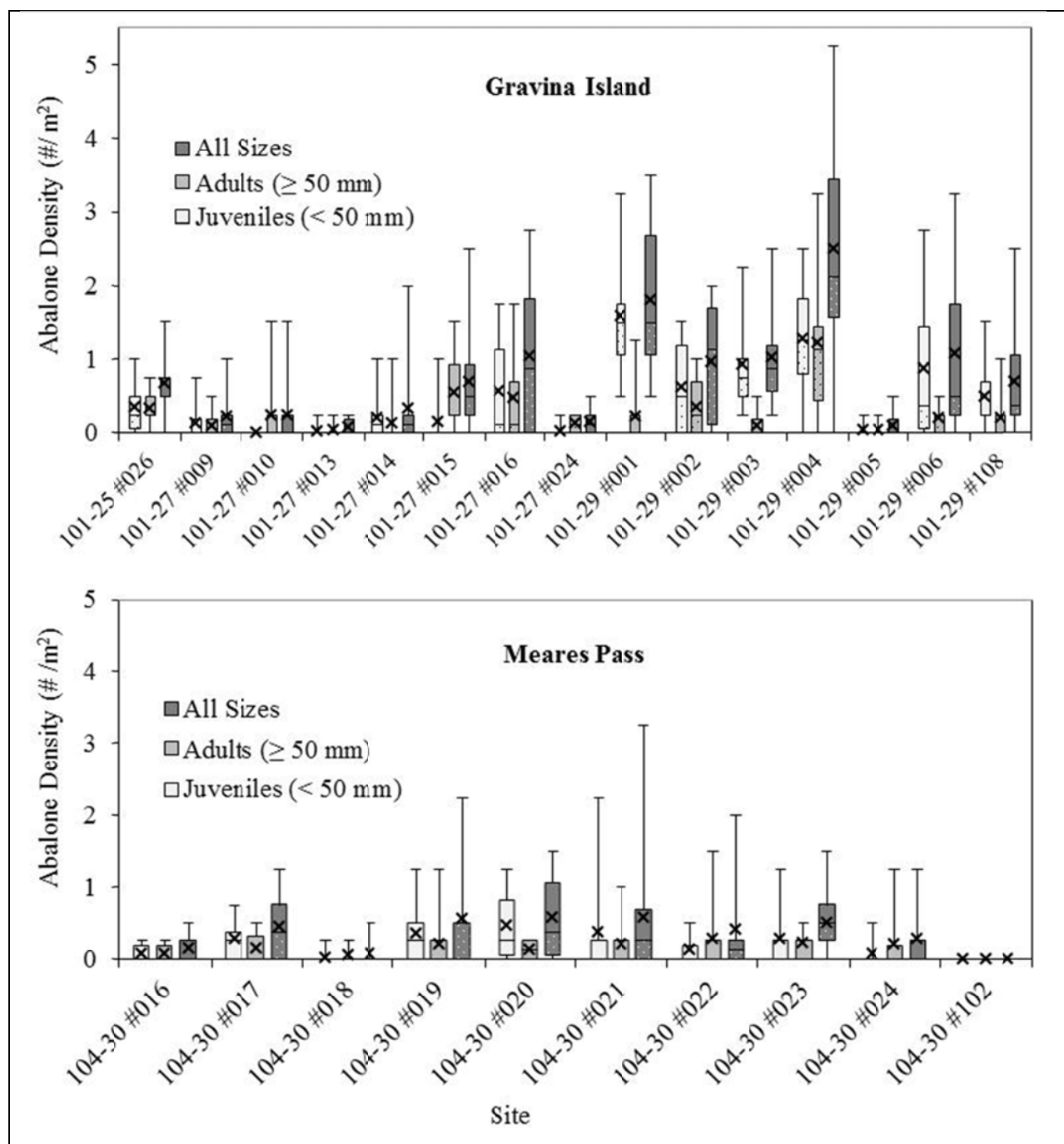


Figure 22.—Box and whisker plots of absolute abalone densities observed within 1x4 m² quadrats during transect surveys, summarized by study area, site, and size class. Size classes were attributed post hoc based on length measurements (and estimates) for each individual. The bottom (stippled pattern) and top of each box are the first and third quartiles, respectively, and the horizontal line inside the box is the second quartile (i.e., the median). The mean is indicated by an “x”, and the positive and negative whiskers extend to the maximum and minimum quadrat density values, respectively.

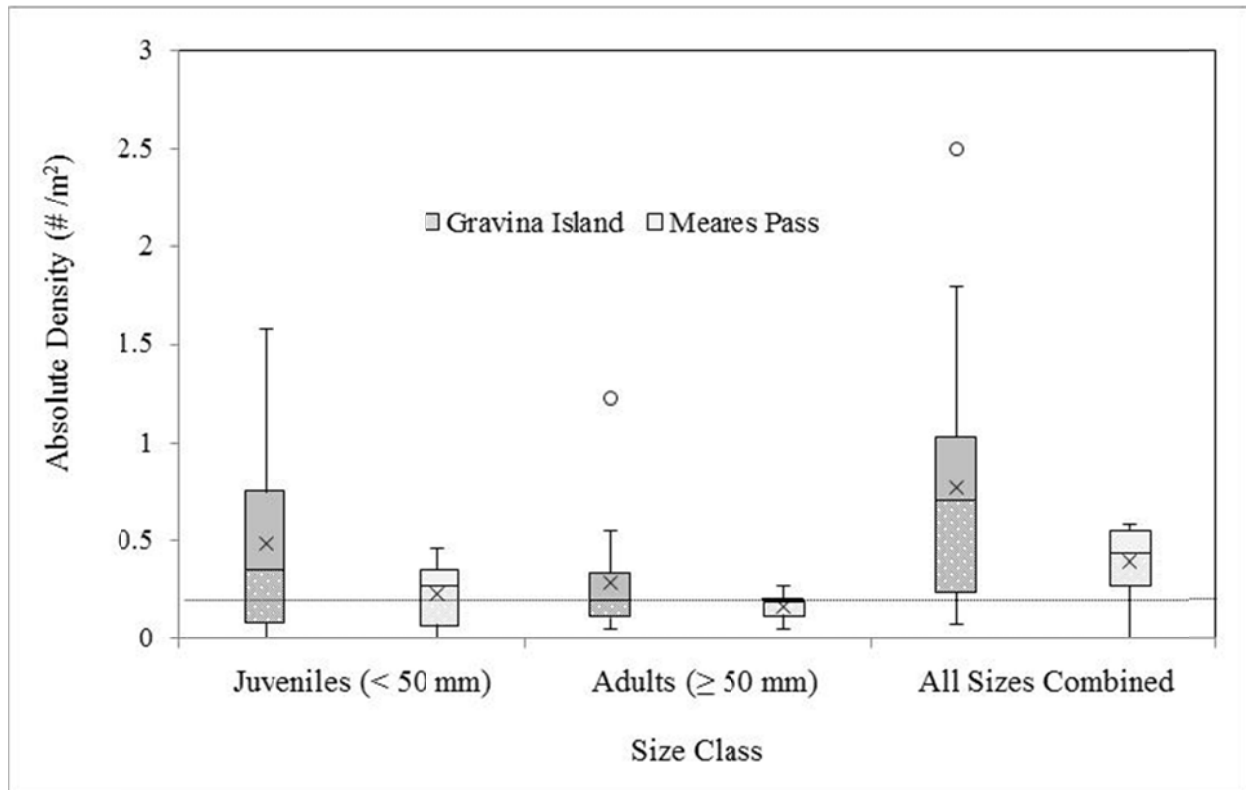


Figure 23.—Box and whisker plots of absolute density of abalone by size class and study area (replicate = site). The dotted horizontal line represents the mean density threshold density for recruitment failure of $0.2/\text{m}^2$ estimated by Babcock and Keesing (1999) and used as a Minimum Viable Population density for red abalone in California's Abalone Recovery and Monitoring Plan (CDFW 2005). The bottom (stippled pattern) and top of each box are the first and third quartiles, respectively, and the horizontal line inside the box is the second quartile (i.e., the median). The mean is indicated by an "x", and the positive and negative whiskers extend to the maximum and minimum quadrat density values, respectively.

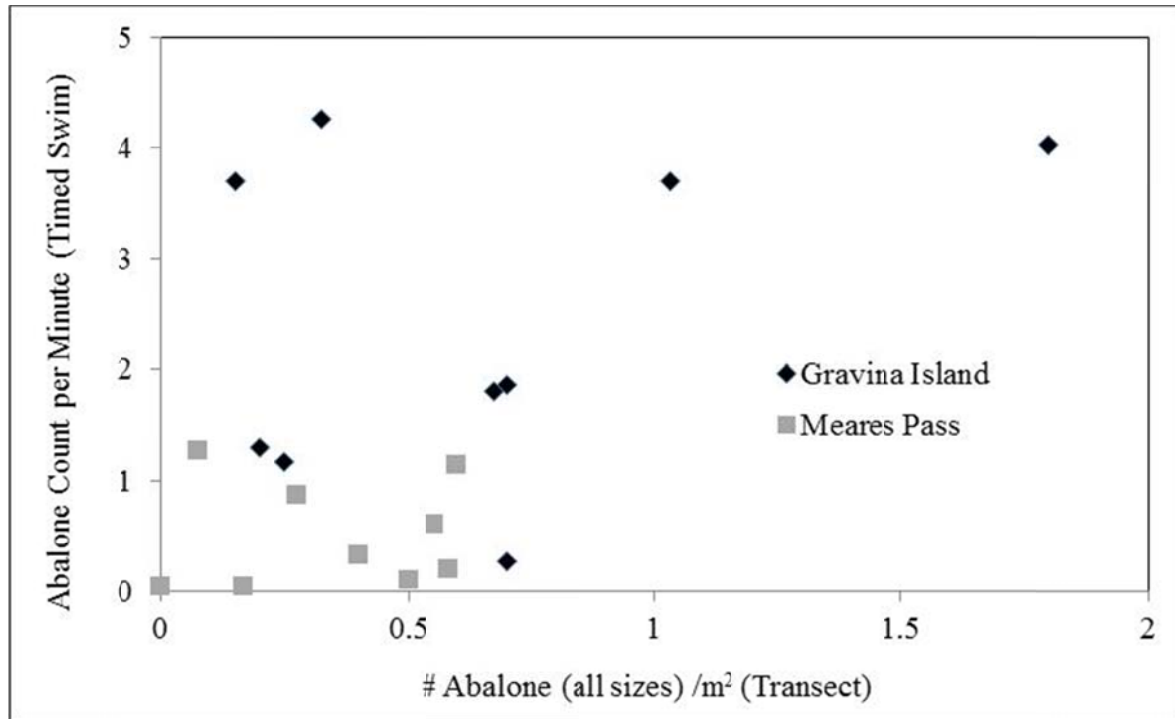


Figure 24.—Scatterplot of abalone relative density (timed swims) vs. absolute density (transects), by study area, with sites as replicates.

APPENDIX A. HISTORICAL ADF&G SURVEYS

The abalone survey dataset (ADF&G unpublished data) is comprised of length-frequency data collected at 141 sites in Southeast Alaska, mostly around Dall Island and southwestern Prince of Wales Island. Surveys were conducted irregularly during 11 years from 1975–1997; some sites were surveyed multiple times within and among years. Surveys were conducted by at least 10 individual observers (mostly ADF&G staff), with the majority of surveys were conducted by two divers, D. Blankenbeckler and R. Larson. Unfortunately, the original datasheets and important survey metadata are either missing or were never documented for many dives, including the primary purpose of a dive (or research cruise), observer name(s), number of observers/collectors, and detailed methodology (e.g., target size classes, search strategy). This information is important for calculating a standardized relative density metric (i.e., count of abalone collected per minute per dive; hereafter CPM) to assess differences in relative abundance within and among sites. To fill as many metadata gaps as possible, we searched electronic and hardcopy records and consulted key ADF&G personnel involved in the original surveys (R. Larson and T. Koeneman, fishery biologists (retired), Alaska Department of Fish and Game, Ketchikan; personal communication). Many unknowns remain, however, and we recommend a more thorough investigation. Despite these uncertainties in the abalone dataset and the more limited spatial and temporal coverage relative to the sea urchin and sea cucumber datasets, overall it is more relevant to the current study because abalone were the target species and data collection was far more standardized. Furthermore, the historical abalone dataset presents a valuable opportunity to assess the relative change in abalone abundance over a 20–25 year period using fishery-independent data. Currently, the only estimate for the magnitude of decline of abalone populations in Alaska is based on catch-per-unit-effort (CPUE) data from the commercial fishery (Woodby et al. 2000). Using CPUE as a proxy for population size is fraught with problems, so re-surveying sites that were first surveyed in 1981 (one of the peak years of the commercial fishery [1979–1981]) using similar CPM methods would provide, for the first time, a fishery-independent estimate of the magnitude of the abalone population decline.

Apparently, the primary objective for most of the survey dives was acquisition of length frequency data for the purpose of informing management of the commercial and subsistence fisheries (size limits were an important management tool) and secondary objectives included collection of biological (e.g., age and growth, maturity) and CPM data. The age and growth work was accomplished by an intensive tagging study at two sites (Ship Island and Gravina Island) from 1979 to 1981 (Blankenbeckler and Larson 1980; Woodby et al. 2000). The length frequency survey data not used for the tagging study have not been published yet, so the site selection and methods that were used are described as follows, as best as they can be reconstructed.

It is unclear exactly how specific survey areas and sites were chosen at the study area and site level (i.e., randomly, haphazardly, systematically, arbitrarily), but we think it is likely that the survey areas were chosen based on their known use by commercial or subsistence fishers. At the site level, at least some were chosen by default from the fishing locations of commercial abalone divers aboard fishing vessels that were actively harvesting abalone. ADF&G staff joined commercial fishing expeditions on several occasions and conducted surveys wherever the divers were harvesting. It is unclear how often, but at least some of the time during these surveys, the ADF&G diver onboard surveyed a site after the commercial divers had harvested the location, so

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we have to assume that the size frequency and count per minute data were biased low. Other surveys were completely fishery-independent, conducted by ADF&G staff aboard ADF&G research vessels. It is not clear how sites surveyed during these cruises were chosen, but we believe that they were probably chosen arbitrarily, perhaps visually (e.g., appeared to have favorable abalone habitat from the sea surface), or from exploratory dives or intelligence from commercial fishers, and consideration was surely given to logistical feasibility (e.g., wave exposure). The geographic accuracy and precision of the dive site coordinates were relatively low by modern standards, due to lack of Global Positioning Systems (GPS) at the time. Coordinate fixes were presumably obtained either by marking the approximate location of the dive on a nautical chart (of which reference scales vary greatly, and are generally less than 1:60,000 except for harbors), or by LORAN. GPS was presumably used to obtain coordinate fixes during the 1997 survey, but it is unknown if differential correction was applied in order to reduce the horizontal accuracy from approximately 100 m to 10 m.

Historical length-frequency abalone surveys were conducted using the following methods, reconstructed to the best of our ability (T. Koeneman and R. Larson, personal communication). For most dives, the objective was for a single diver to collect as many abalone as possible using one standard SCUBA tank of air (oxygen-enhanced air was not used). At the dive site, a single SCUBA diver would enter the water and immediately begin searching for abalone to collect. A second diver in full SCUBA gear remained onboard and functioned as a safety diver in case of emergency, and a skiff tender piloted the dive skiff. The diver/observer was permitted complete freedom in how and where to search (e.g., depth, swimming speed and direction), and would target what they considered to be optimal abalone habitat. The minimum size class targeted is unknown, but based on a histogram of the combined historical length-frequency data, we believe it was probably in the range of 30–50 mm (data range: 17–160 mm). Abalone were either plucked from the substrate with a tool (usually a pry bar designed specifically for abalone harvesting) or by hand without a tool, if the animal was not clamped down on the substrate (which it would often do if it sensed the diver). During dives conducted for the primary purpose of tagging, severed arms of the sea star *Pycnopodia helianthoides* (an important predator of abalone that elicits an escape response) were occasionally used to flush small abalone from crevices, but apparently this technique was not used during relative density/length frequency surveys (R. Larson, personal communication). The diver would generally search for and collect abalone until the available compressed air in his SCUBA cylinder began to run low (approximately 500 pounds per square inch), at which time he would surface and hand the collection bag to topside staff for measuring. Dive start and end times were recorded, as well as notes about the habitat and vegetation encountered during the dive. Onboard the skiff, the abalone would be measured along the longest maximum shell dimension to the nearest millimeter, then most, if not all, abalone would be returned to the seafloor in the general vicinity from which they were taken. If the diver was accompanying a commercial fishing expedition, the legal-sized abalone would often be given to the fishermen.

A thorough treatment of the CPM metric (count of abalone collected per minute per dive) derived from historical abalone survey data is warranted both for comparisons of historical data with itself (for survey planning and index site selection), as well as for future comparisons of

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historical data with data obtained from the present study. To guide index site selection for the present study, we calculated CPM for each sampling event (i.e., dive) in the historical dataset and assigned the maximum value recorded at a given site to that site (most sites were surveyed only once, but a subset were surveyed multiple times). The results were plotted in a Geographic Information System (GIS) for visual inspection. There were often several assumptions made when calculating the CPM for a given dive, all of which have an influence on the reliability of the results. These assumptions included the survey purpose, number of observers/collectors, and specific methodological details (e.g., search image target size, search speed, depth range covered, precision of dive duration recorded, whether additional tasks were also performed). Because of the assumptions about methodological details, CPM values should be treated as a minimum estimate (e.g., counts would have been higher per minute if divers were not conducting additional tasks while collecting abalone). Furthermore, there were many dives in which no observer name(s) was stated for a given dive; this was problematic because the relative density metric needed to be standardized by dividing the count per minute value by the number of observers/collectors. In these cases, we calculated a count per minute per dive under the assumption that the data were collected by only one diver. These calculated values were artificially high if there was indeed more than one collector, so these values were considered “unconfirmed” and used secondarily to “confirmed” data in which the number of observers was known.

Appendix A2.—Description of ADF&G’s sea cucumber and sea urchin surveys in which abalone data were opportunistically collected.

The methods used for sea urchin and sea cucumber surveys were very similar except for the target species, so both datasets were combined and will be described together here. The sea urchin survey dataset is comprised of approximately 6,044 person-dives by 39 divers during 3,022 dives of 743 survey sites (transects) within 34 survey areas over 23 unique years. The sea cucumber survey dataset is composed of approximately 6,160 person-dives by 33 divers during 3,080 dives of 753 survey sites within 37 survey areas over 26 unique years. The methods used for sea urchin and sea cucumber surveys have been described in detail within several ADF&G reports (sea urchins: e.g., Davidson et al. 1992; Hebert and Larson 2000; sea cucumbers: e.g., Larson et al. 1995; Hebert 2012), but are stated here in brief. Generally between 14–40 dive survey sites per fishery area (depending upon the length of shoreline within the fishery area; more shoreline = more transects) were systematically spaced within a fishery area and re-surveyed every 3 years for sea cucumbers and between every 3–6 years for sea urchins. During a survey, two SCUBA-equipped divers would count sea urchins within a swath along a “virtual transect” (i.e., no permanent transect line or temporary transect tape was deployed) oriented perpendicular to the prevailing depth contour, from the waterline to a maximum depth of 50 feet (15.2 m). Swaths were one meter wide for sea urchin surveys and two meters wide for sea cucumber surveys. On approximately half of these dives, divers would also collect sea urchins or sea cucumbers (depending on the survey target species) for subsequent measurement at the surface. In several fishery areas, sea urchin surveys are combined with sea cucumber surveys, and both species are counted and collected on the same dive.

There was no standardization of ancillary data collection for abalone during sea urchin or sea cucumber survey dives until 2014. Until then, abalone counts or presence/relative abundance information during these sea urchin surveys was opportunistically recorded at the discretion of the diver (i.e., null data were not equivalent to absence). A dedicated data field was included on the field datasheet beginning in 2014, and divers were instructed to note the presence or absence of any live abalone and to count them, if possible, provided that doing so would not interfere with the primary objective of surveying sea urchins. Because pinto abalone are often relatively inconspicuous due to their camouflage and relatively small size (especially relative to the search image size of the target organism, sea urchins), even a data value of “not present” in the 2014 data should not be considered a true absence, because they could have easily been overlooked. Therefore, unless an actual count was recorded, the 2014 data should conservatively be considered “presence only” data, albeit in a more standardized way than in prior years. For all years, divers typically noted the number of abalone observed or some indicator of relative abundance in the comment field of their datasheets. In an attempt to derive a semi-quantitative index metric to determine which dive sites harbored the most abalone, at least in the past, we inspected all of the notes in the sea urchin survey database and extracted any available quantitative or qualitative information about abalone abundance. When actual counts weren’t reported, expert judgment was used to estimate [conservatively] approximately how many abalone a diver may have seen based on their qualitative comments. Assigning a count to non-quantitative comments was a subjective exercise, so the count accuracy should be considered low. However, given the significant sample size and spatial and temporal extent of the dataset, we believe that there is value in summarizing these data.

APPENDIX B. TIMED SWIM PROTOCOL

Relative Density (Timed Swim) Surveys

Purpose

To obtain an estimate of the relative change between extant and historical abalone populations in two historical abalone strongholds, to complement the fishery-dependent CPUE-based estimate currently used

Objective

To determine the relative density and size frequency of extant pinto abalone populations in two historical abalone strongholds

Metrics

- # of abalone observed per diver per minute
- Abalone length (maximum shell dimension, in mm)
- Abalone depth distribution (standardized by search duration per depth strata)

Materials

- Global Positioning System (GPS) with either real-time differential correction or Wide Area Augmentation System correction enabled
- Dive slate + pencil (1)
- Datasheet (1)
- Vernier calipers
- Pelican floats (2)
- Depth/time gauge (1)
- Stopwatch (if not integrated into depth/time gauge)

Personnel

- SCUBA equipped divers (2)
 - One diver highly skilled in abalone surveys will be the observer and data recorder
 - The other diver will have no duties other than to serve as a buddy/safety diver
- dive/skiff tender (1)

Sample Unit Size / Sample Size

- One variable-sized (~50-200 m²) timed swim survey per index site; $n = 10$ index sites per study area)
- One-time only, for 2 days during summer

Methods

1. Enter as much datasheet header information as possible, including study area, site number, tide-correction, and names of observer/recorder and buddy
2. Navigate as closely as possible to the index site using a GPS (ensure WAAS is enabled); zoom in to the finest scale possible with the GPS (i.e., 20 ft), then drop off the dive team in the 10–15 depth zone nearest to the point
3. Upon reaching the bottom, the observer will assess the suitability of abalone habitat.

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- a. If abalone habitat (defined here as substrate grain size $\geq$ cobble) is encountered, the observer will record the dive time from their dive computer (in minutes) in the “roving time start” field, then start their stopwatch and begin the timed swim search.
 - b. If abalone habitat is not encountered within ~10 m of the original location, search in the most promising direction. When appropriate habitat is found, the divers will deploy a Pelican float so the skiff tender to obtain a GPS fix for the actual starting location, and then the observer will record the dive time from their dive computer (in minutes) in the “roving time start” field, and begin the timed swim search
4. Search parameters:
 - a. Initially focus the search in the typical depth zone of maximum abalone abundance (10–20 ft depth, relative to MLLW), but let the presence of abalone and location of optimal habitat be the primary driver of where to search; intensively search the immediate area for other abalone once an abalone is found
 - b. Use a search image for abalone > 50 mm in maximum shell dimension, but record data for all abalone observed
 - c. Do not turn over or move rocks to search for abalone
 - d. If divers lose visual contact with each other, the observer should stop the stopwatch and attempt to relocate their buddy; if the buddy cannot be found within one minute, they should ascend to the surface and re-establish contact; once contact is re-established, divers should descend to the seafloor and re-start the stopwatch when ready to begin searching again
5. When the observer sees an abalone, he/she will:
 - a. pause the stopwatch clock
 - b. measure the abalone with Vernier calipers to the nearest millimeter
 - i. If the abalone is in an inaccessible location (e.g., in a crevice), estimate the length of the abalone to the nearest millimeter and flag the measurement as an estimate
 - c. record the depth of the abalone (uncorrected to MLLW)
6. After 30 minutes of searching:
 - a. stop the stopwatch
 - b. deploy a pelican float to mark the endpoint of the search
 - c. record:
 - i. the dive time from the dive computer in the “roving time end” field
 - ii. the stopwatch end time
 - iii. depth range searched
 - iv. habitat variables (% suitable abalone habitat [to nearest 10%], dominant substrate types, dominant vegetation types and percent cover
 - v. dive conditions (visibility, surge level, light level)
 - vi. ancillary ecological data (relative abundance of red sea urchins, sea otter presence and sign)
 - vii. any other relevant comments
7. Terminate the dive and board the skiff
8. Obtain a GPS fix for the Pelican float indicating the end point of the search
9. Complete all remaining header data on the datasheet (lat/long, dive time start and end) GPS positions for each pelican float

Appendix B2.–Field datasheet for timed swim surveys.

NMFS Abalone Survey Roving Timed Swim Datasheet														
Site Name: _____					Date (m/d/yyyy): ____ / ____ / 2016									
Recorder Name: _____					Buddy Name: _____									
Start Latitude: 5 ____ . ____ °					Longitude: -135. ____ °									
End Latitude: 5 ____ . ____ °					Longitude: -135. ____ °					Tide Corr.: _____				
Dive Time Start: _____					Dive Time End: _____ (hhmm, 2400 hr format)									
Roving Time Start (minutes): _____					Roving Time End: _____					Depth Range: _____				
Ab #	Size (mm)	Z (ft)	Ab #	Size (mm)	Z (ft)	Ab #	Size (mm)	Z (ft)	Ab #	Size (mm)	Z (ft)	Ab #	Size (mm)	Z (ft)
1			21			41			61			81		
2			22			42			62			82		
3			23			43			63			83		
4			24			44			64			84		
5			25			45			65			85		
6			26			46			66			86		
7			27			47			67			87		
8			28			48			68			88		
9			29			49			69			89		
10			30			50			70			90		
11			31			51			71			91		
12			32			52			72			92		
13			33			53			73			93		
14			34			54			74			94		
15			35			55			75			95		
16			36			56			76			96		
17			37			57			77			97		
18			38			58			78			98		
19			39			59			79			99		
20			40			60			80			100		
Comments:														

APPENDIX C. TRANSECT PROTOCOL

Absolute Density (Quadrat) Surveys

Purpose

To initiate assessment of trends in pinto abalone populations using repeatable methods within multiple areas of Southeast Alaska

Objectives

To determine the absolute density and size frequency of extant pinto abalone populations in two widely-spaced study areas in Southeast Alaska, one with and one without sea otters present

Metrics

- Maximum shell dimension (mm)
- # abalone ≥ 50 mm max shell dimension per square meter
- # abalone < 50 mm max shell dimension per square meter

Materials

- Global Positioning System (GPS) with either real-time differential correction or Wide Area Augmentation System correction enabled
- dive slate + pencil (2)
- datasheets (2)
- Vernier calipers (1)
- 1m² PVC quadrat (2)
- Compass (1)
- Flashlight (2)
- dive computer with depth gauge and timer (2)
- transect tape (≥ 1 , depending on transect tape length and width of seafloor slope from 0 to 30 ft depth), with one 5-6 lb weight attached to end of tape
- clip-on temporary weights for anchoring transect tape (5)
- Pelican float (1)

Personnel

- SCUBA equipped divers (2)
- dive/skiff tender (1)

Sample Size / Sample Unit Size

- One transect 2 meters in width
- 40–60 1-m² square subsamples per transect (these quadrats may be aggregated post hoc into 2-m² sampling units)
- $n = \geq 10$ transects per study area

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Frequency

- $n = 1$ (Summer 2016)
- Follow-up surveys in subsequent years, pending availability of funding

Methods

1. Plan order of index site sampling
 - a. If possible, plan to survey wave-exposed index sites at the highest tide practical in order to minimize surge at shallow working depths (up to 0 ft MLLW)
2. Dive preparation
 - a. Prior to the dive, fill out as much datasheet header information as possible, including study area, site number, tide-correction, starting and ending target depths, transect side sampled (from perspective of looking from offshore to onshore) and diver initials
 - b. Equip the divers with 2 quadrats, 2 slates and datasheets (slates should have pencil, compass and dive computer attached), 2 sets of Vernier calipers, 2 flashlights, pelican float, transect tape(s), and weights for securing transect tape
3. Navigation
 - a. Navigate the skiff to the index site using the starting point in the GPS (ensure WAAS or differential correction is enabled)
 - b. Run a virtual transect in the skiff, from the starting point offshore across the depth contours; estimate how long the transect is and choose the most appropriate transect tape for the divers to carry (e.g., if the transect appears to be 30 m long on the surface, use a transect tape ≥ 50 m long; if the transect is 60 m long on the surface, use a 100 m tape).
 - c. Navigate back to the index site as closely as possible, zooming in to the finest scale possible with the GPS (i.e. 20 ft), then drop off the dive team as close to the shore as possible and simultaneously mark a waypoint where the divers were dropped off (to be transcribed onto divers' datasheets after dive)
4. Transect setup
 - a. On the surface, divers will take and record a compass bearing perpendicular to the shoreline and prevailing depth contours
 - b. One diver will place the weighted 0 m end of a transect tape at the 0 ft (relative to Mean Lower Low Water, MLLW) depth contour, and then pay out the transect tape while swimming offshore and carefully following the pre-selected bearing until the 30 ft depth contour is reached
 - i. If the transect is in a shallow embayment and the 30 ft depth threshold cannot be reached before the seafloor begins to rise to the other shoreline, the end of the transect will be placed at the deepest depth reached (which may not be exactly midway between opposite shorelines).
 - c. The other diver will follow behind the diver paying out the transect, weighting the transect so that it lies mostly flat along the seafloor (e.g., the tape should not be suspended in mid-water over bathymetric features)

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- d. Place temporary weights (e.g., rocks) on the transect spool once the 30 ft depth contour is reached, and deploy a pelican float (do not attach it to the transect tape);
5. Transect surveying
 - a. Divers will orient themselves on opposite sides of the transect tape and face onshore; when ready to begin sampling, record dive time (in minutes) from dive computer
 - b. Beginning at the 30 ft depth contour, both divers will place one edge of their quadrats along the transect tape (contiguous with the other diver's quadrat), and then sample within their respective quadrats
 - i. Divers may choose to stagger sampling temporally so they do not crowd each other, but sampled quadrats must always be directly adjacent to each other
 - ii. In the event of steep slopes in which the quadrat will not remain in place due to gravity, divers will assist each other by holding the quadrat in place while the other diver surveys
 - c. Quadrat sampling
 - i. Thoroughly search for abalone within the 1 m² quadrat
 1. use a search image target size of ≥ 30 mm (maximum shell dimension)
 2. use flashlights to illuminate dark areas (e.g., crevices) whenever necessary
 3. do not move or turn over rocks, but move or remove vegetation if necessary
 - ii. Measure each accessible abalone (even if they are smaller than the search image target size) to the nearest millimeter using Vernier calipers and record on datasheet
 1. **DO NOT CUT ABALONE WITH CALIPERS—THEY MAY DIE**
 2. If abalone is inaccessible, estimate length to the nearest millimeter and flag measurement on the datasheet with an asterisk (*)
 - iii. For each abalone, record whether its behavior is “cryptic” (= difficult or impossible for you to measure with calipers) or “exposed”
 - iv. Record data for habitat occurring within the 1 m² quadrat
 1. Depth of upper and lower edges of quadrat (in feet, uncorrected to MLLW)
 2. Primary and secondary substrate type, by percent cover
(ABBREVIATION)
 - a. Bedrock (**RCK**)
 - b. boulder [0.256 - 4.096 m] (**BLD**)
 - c. cobble [6.4 < 25.6 mm] (**CBL**)
 - d. gravel/pebble/granule [2 < 64 mm] (**GRV**)
 - e. non-living shells (**SHL**)
 - f. shell hash (**HASH**)
 - g. sand [0.0625 - <2 mm] (**SND**)
 - h. mud (**MUD**)
 - i. silt (**SLT**)

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3. number of crevices (crevice = a space you can insert outstretched hand into)
 4. number of red sea urchins >60 mm test diameter
 5. vegetation percent cover, by guild (to nearest 5–10%)
 - a. canopy-forming kelps (*Macrocystis*, *Nereocystis*, and *Alaria fistulosa*)
 - b. sub-canopy kelps (0.1–1.5 m tall); e.g., *Laminaria*, *Agarum*, *Costaria*, *Cymathere*, *Pleurophycus*)
 - c. foliose red algae (0.1–0.5 m tall); e.g., *Mazzaella*, *Opuntia*, *Constantinea*, *Rhodymenia*
 - d. “turfy” red algae (< 0.1 m tall); e.g., *Mastocarpus*, *Chondracanthus*)
 - e. Articulated coralline algae; e.g., *Corallina*, *Bossia*
 - f. Encrusting coralline algae
 - g. Green algae; e.g., *Codium fragile*, *Codium setchellii*
 6. Record kelps and dominant red/green algal taxa to highest taxonomic resolution, if known
 7. Percent cover of encrusting/turf/sessile invertebrate cover; e.g., calcareous tubeworms, bryozoans, hydroids, anemones
 8. Surge index
 - a. 0—not noticeable
 - b. 1—noticeable but doesn’t or only mildly affects work
 - c. 2—moderately affects work
 - d. 3—strongly affects work
 - v. After sampling quadrat (and following diver has placed adjacent quadrat, if applicable), move quadrat upslope to the next 1 ft depth contour
 1. When the slope of the seafloor along a transect is steep, it is possible that fewer than thirty 1m² quadrats per diver will be sampled because a single quadrat may span >1 ft of depth (e.g., on a “wall”). In the event that the deep side of the quadrat is >1 ft deeper than the shallow side, the next quadrat will simply be placed upslope immediately adjacent to the previous quadrat.
 2. Continue quadrat placement process for each 1 ft depth contour (e.g., starting at -30 ft, the next quadrat will be placed at -29 ft, then -28 ft, etc., until the last quadrat is placed at -1 ft), or until excessive surge makes sampling impractical, whichever comes first
 - vi. Record dive time from dive computer (in minutes) after last quadrat is completed
6. Wrap-up
- a. Each diver shall review their own datasheet for legibility and completeness, and amend if necessary
 - b. Skiff operator will record the coordinates of the transect endpoint (where the pelican float was deployed) and dive start/stop times, and review each diver’s datasheet for legibility and completeness
7. Move on to next index site and repeat

Appendix C2.–Transect datasheet, side 1.

NMFS Abalone Survey Transect Datasheet– Side 1										
Site Name: _____ Site #: _____ Date: ____ / ____ / 2016 Tide (ft): _____										
Recorder: _____ Buddy: _____ Transect Side: Left / Right Bearing (°): _____										
Transect Start/End (min.): ____ / ____ Vis. (ft): _____ Dive Time Start/End (hhmm): ____ / ____										
Start Lat: 5 ____ . _____ ° Lon: -13 ____ . _____ ° / End Lat: 5 ____ . _____ ° Lon: -13 ____ . _____ °										
Quadrat #	1L	1R	2L	2R	3L	3R	4L	4R	5L	5R
Meter (lower)										
Depth (lower)										
Canopy %										
<i>Macrocystis</i>	+	--	+	--	+	--	+	--	+	--
<i>Nereocystis</i>	+	--	+	--	+	--	+	--	+	--
Subcanopy %										
<i>Agarum</i>	+	--	+	--	+	--	+	--	+	--
Abalone # 1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
Green algae %										
Red algae %										
<i>Constantinea</i>	+	--	+	--	+	--	+	--	+	--
Art. coralline %										
Encrust. cor. %										
Sessile Invert %										
1° Substrate										
2° Substrate										
# Crevices										
# Red Urchins										
# Green Urchins										
Surge Index										
Comments:										

Appendix C3.–Transect datasheet, side 2.

NMFS Abalone Survey Transect Datasheet - Side 2										
Site Name: _____			Site #: _____			Date: ____ / ____ / 2016				
Recorder: _____			Buddy: _____			Transect Side: Left / Right				
Quadrat #	6L	6R	7L	7R	8L	8R	9L	9R	10L	10R
Meter (lower)										
Depth (lower)										
Canopy %										
<i>Macrocystis</i>	+	--	+	--	+	--	+	--	+	--
<i>Nereocystis</i>	+	--	+	--	+	--	+	--	+	--
Subcanopy %										
<i>Agarum</i>	+	--	+	--	+	--	+	--	+	--
Abalone # 1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
Green algae %										
Red algae %										
<i>Constantinea</i>	+	--	+	--	+	--	+	--	+	--
Art. coralline %										
Encrust. cor. %										
Sessile Invert %										
1° Substrate										
2° Substrate										
# Crevices										
# Red Urchins										
# Green Urchins										
Surge Index										
Comments:										

APPENDIX D. INDEX SITE LOCATIONS

Appendix D1.–Index site location information for transects.

Starting and ending geographic coordinates for transects at each index site. All coordinates are in decimal degrees, NAD 83 datum. The magnetic bearing listed for each transect is from the onshore starting point to the offshore ending point. Transects were assumed to be straight lines between the start and end point.

Study Area	ADF&G Sub-district	Site #	Transects				
			Start Latitude	Start Longitude	Magnetic Bearing (°)	End Latitude	End Longitude
Gravina Island	101-25	26	55.11013	-131.73842	315	55.11017	-131.73845
		9	55.18982	-131.71207	70	55.18974	-131.71277
		10	55.17544	-131.71939	60	55.17518	-131.72083
		13	55.13544	-131.74303	70	55.13585	-131.74350
		14	55.13942	-131.73347	270	55.13944	-131.73329
		15	55.15675	-131.74074	70	55.15674	-131.74051
		16	55.16451	-131.72806	130	55.16460	-131.72812
		24	55.14528	-131.71913	100	55.14577	-131.72061
	101-29	1	55.12836	-131.75240	200	55.12846	-131.75217
		2	55.13880	-131.76863	180	55.13880	-131.76860
		3	55.13828	-131.77795	160	55.13867	-131.77834
		4	55.15314	-131.78778	270	55.15307	-131.78735
		5	55.16034	-131.78789	235	55.16036	-131.78717
		6	55.16265	-131.80139	235	55.16268	-131.80121
		108	55.14375	-131.78076	240	55.14349	-131.78165
		16	55.18456	-133.23393	320	55.18542	-133.23419
		17	55.18489	-133.22556	330	55.18530	-133.22577
		18	55.18689	-133.21606	175	55.18723	-133.21591
		19	55.18897	-133.20779	350	55.18921	-133.20752
		20	55.20098	-133.19386	50	55.20102	-133.19366
		21	55.20717	-133.20152	250	55.20707	-133.20119
		22	55.20610	-133.20233	270	55.20610	-133.20195
		23	55.20240	-133.22160	90	55.20227	-133.22198
		24	55.20072	-133.22511	90	55.20062	-133.22444
		102	55.16417	-133.22626	180	55.16356	-133.22664
Meares Pass	104-30	16	55.18456	-133.23393	320	55.18542	-133.23419
		17	55.18489	-133.22556	330	55.18530	-133.22577
		18	55.18689	-133.21606	175	55.18723	-133.21591
		19	55.18897	-133.20779	350	55.18921	-133.20752
		20	55.20098	-133.19386	50	55.20102	-133.19366
		21	55.20717	-133.20152	250	55.20707	-133.20119
		22	55.20610	-133.20233	270	55.20610	-133.20195
		23	55.20240	-133.22160	90	55.20227	-133.22198
		24	55.20072	-133.22511	90	55.20062	-133.22444
		102	55.16417	-133.22626	180	55.16356	-133.22664

Appendix D2.–Index site location information for timed swims.

Starting and ending geographic coordinates for timed swims for each index site. All coordinates are in decimal degrees, NAD 83 datum. Straight lines between the start and end point should not be assumed.

Study Area	ADF&G Sub-district	Site #	Timed Swims			
			Start Latitude	Start Longitude	End Latitude	End Longitude
Gravina Island	101-25	26	55.11016	-131.73839	55.11089	-131.73799
		9	55.18986	-131.71249	55.19047	-131.71208
	101-27	10	55.17517	-131.72044	55.17610	-131.72057
		14	55.13967	-131.73335	55.14022	-131.73344
		15	55.15683	-131.74072	55.15698	-131.74121
		16	55.16475	-131.72797	55.16435	-131.72826
		24	55.14561	-131.72038	55.14581	-131.72038
	101-29	1	55.12867	-131.75264	55.12898	-131.75301
		108	55.14366	-131.78174	55.14022	-131.78344
Meares Pass	104-30	16	55.18450	-133.23410	55.18469	-133.23455
		17	55.18491	-133.22568	55.18491	-133.22568
		18	55.18687	-133.21603	55.18723	-133.21616
		19	55.18922	-133.20840	55.18900	-133.20749
		20	55.20160	-133.19432	55.20164	-133.19431
		21	55.20722	-133.20099	55.20664	-133.20174
		22	55.20608	-133.20212	55.20573	-133.20189
		23	55.20227	-133.22198	55.20277	-133.22266
		24	55.20073	-133.22484	55.20055	-133.22551
		102	55.16351	-133.23021	55.16323	-133.23093

APPENDIX E. METHODS EVALUATION

Survey Design and Method Evaluation

Study Design

This study was only the second in Southeast Alaska to attempt a rigorous estimate of abalone density (with the first being our study in Sitka Sound during 2015–2016; Bell et al. *in prep*). This study (and the Sitka study) provided a first glimpse of density estimates for abalone populations in Southeast Alaska, which helped fill a major knowledge gap identified in the ESA status review (Busch et al. 2014). In both studies, prime abalone habitat was targeted, so none of the density estimates (and to a lesser extent, size structure characteristics) should be considered representative of other areas, or even their respective study areas. The emphasis on known or suspected sites with relatively high abalone density was by design, in order to establish a benchmark “best-case scenario” for abalone aggregations/populations in Southeast Alaska. Using historical relative abundance data was apparently an effective strategy for site selection in this study, because abalone were observed at each of the 25 index sites established, albeit at very low densities at two sites in Meares Pass and one site at Gravina Island. Given the highly patchy nature of abalone aggregations and presumed low overall density, this success rate probably would not have occurred if a randomized or systematic site selection process had been used instead. We chose this approach because the emphasis of the study was on implementing a long-term monitoring program, not a stock assessment. If a systematic or random sampling survey design would have been used instead for either study, the mean density estimates would have almost certainly been much lower.

We recognized that having only one study area replicate in each sea otter “treatment” (areas with sea otters present vs. sea otters absent) prevents generalization and extrapolation of results about the effect of sea otters on abalone populations, but this was a necessary concession due to limitation of staff and funding resources. Strictly speaking, any comparison between the two study areas will only illuminate the difference (if any) between the two areas, which could be due to any number of factors. However, if additional study areas (replicates) were surveyed in sea otter and non-sea otter areas in the reasonably near future (i.e., before any potential confounding temporal effects could be invoked), the combined data could be analyzed to address sea otter effects in a more scientifically rigorous fashion (i.e., a “natural” experiment). Nevertheless, from a practical standpoint the data obtained in each study area were considered “pilot data” for representing sea otter-occupied and non-occupied treatments, for the purpose of informing future studies in which a more robust survey design would be used to rigorously analyze the question of sea otter effects.

Size Structure

As is the case for many data-limited fish stocks, size frequency data provided the largest benefit per unit of survey effort in terms of output of useful information. Maximum shell length was used as a proxy for size in this study, and we were able to gain important insights into the population status via age structure derived from length frequency data, as well as gauge recruitment to the population, and estimate whether human fishing effects were likely. Length frequency data were collected using both the timed swim and transect methods, but the timed swim method was far more efficient in terms of time, effort, overall cost, and total number of

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individuals sampled. When standardized to the number of divers, timed swims took approximately 50% less time to complete than transects at Meares Pass, and approximately 25% less time to complete at Gravina Island. This in combination with a much higher number of abalone measured per unit time resulted in a larger sample size in each study area, despite timed swims being allocated only 33% of the total diving effort in our study. Given the large number of length data points needed to ensure high precision of length frequency proportions ($n = 510$), the sampling efficiency was obviously an important benefit of timed swims. The length frequency sample size was not robust using either method at Meares Pass, where abalone densities were much lower and survey conditions were more challenging (e.g., high algal diversity and cover).

One of the benefits to our approach of collecting length frequency data using two different methods (timed swims and transects) was that it allowed us to assess whether there were any differences in the results between methods, and specifically whether there were any negative aspects to using the more efficient timed swim method. In our case we considered the length frequency data collected using the transect method to be a more accurate representation of the true size structure present in the “population” (i.e., the portion of the true population not hiding under rocks or so far back in crevices as to be unobservable). We made this assumption because the transect divers spent more time searching per unit area (their 1 m² quadrat), as opposed to the timed swim observer who was allowed (and expected) to search a large amount of seafloor quickly, in order to find and hone in on abalone aggregations.

The primary concern about using length frequency data from timed swims was that the data would be biased negatively for small size classes and positively for large size classes, which if true would confound or complicate interpretation of results. We evaluated the likelihood of this bias by comparing length frequency data from timed swims and transect surveys at the same suite of sites within each study area. The more unstructured nature and [presumed] faster search speed of timed swims relative to transects suggested that smaller individuals would be overlooked in favor of larger individuals, but the results indicated the opposite effect. Although there was a significant difference between length distributions obtained using different methods at Gravina Island (Table 4), the peak counts (assumed here to be the size of full selectivity to sampling methods, per catch curve analysis interpretation) were at smaller size classes for timed swims than for transects at both Meares Pass and Gravina Island (Figure 15). The non-significant test result for differences between methods at Meares Pass was not surprising, and was likely more an effect of low power due to small sample size than the lack of a true effect. There were indeed proportionally more large size classes in the timed swim dataset at Gravina Island, but these did not appear to come at the “expense” of the smaller size classes. Instead, the shape of the histogram exhibited more uniformity among size classes than it did for the transect data. We therefore concluded that the accuracy of the length frequency data obtained from timed swims in this study was not appreciably biased. We were fortunate in this determination because the sample size from timed swims was so much greater than it was for transects, which improved the robustness of our results, all else being equal. That said, the accuracy of length frequency data from timed swims in this study should not be extrapolated to other studies because only one individual (TDW) performed the observer role during all timed swim dives. This individual was highly skilled at searching for abalone (including small individuals) and had a great deal of

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experience conducting abalone surveys in the previous year. This caveat highlights what we view as the most negative aspect of the timed swim method, which is that it is highly observer-dependent and may not necessarily be reliably reproducible.

One of the secondary concerns about length frequency data from timed swims relative to transects was that a higher proportion of the lengths obtained would be estimates, rather than actual measurements, and that any such estimates would result in less accurate length frequency estimates than actual measurements. We suspected this may be an issue because of a presumed lower search effort in difficult-to-inspect cracks and crevices, for the same reason we expected a possible size bias as described above. There was indeed a surprisingly large difference between timed swim and transect methods in the percentage of lengths estimated at Meares Pass, but not Gravina Island (Table 3). We expected a higher proportion of estimated lengths for transects than timed swims in general because of the slower pace and more thorough inspection of cryptic habitats (e.g., crevices, underneath algae) typical of transect surveys, but the large difference between methods at Meares Pass (12% vs 41%; Table 3) between timed swims and transects, respectively, was higher than expected, and suggested the presence of bias. The most striking difference between Meares Pass and Gravina Island was the much higher diversity and abundance of algae at the former, which may have obscured the visibility of the relatively fast-moving timed swim diver more than the slower transect diver. Alternatively, the search technique of the timed swim diver may have subtly evolved or been refined by the time Gravina Island was surveyed on a subsequent date. The difference between timed swims and transects was much smaller at Gravina Island (11% vs. 24%, respectively) and more in line with our expectations. However, lower underwater visibility and much higher algal cover at Meares Pass were probably contributing factors because abalone would have been more difficult to observe in general for faster-paced timed swims, and the effect would have been disproportionately greater as a function of decreasing abalone length. We also expected the percentage of lengths estimated to be positively correlated to the percentage of cryptic abalone, but we could not rigorously test this question. Not enough behavioral observations (cryptic vs. exposed) were made during transects at Meares Pass to determine a robust estimate of the percentage of cryptic abalone, so it is difficult to make any meaningful comparisons of behavior between methods in that study area. However, it was somewhat surprising that for timed swims at Meares Pass, only 12% of the lengths were estimated despite 58% of the abalone observed being classified as cryptic (and therefore presumably more inaccessible and difficult to measure). This will take additional study in the future to resolve.

At Meares Pass, the length frequency distribution was strikingly smaller in 2016 than 1980–1981 or 1986. Very few abalone less than 26 mm length were reported from the 1980–1981 and 1986 surveys, in contrast to a substantial portion of the abalone from the 2016 survey in this size class. A methodological difference (target search image size) may have been the cause for this apparent difference, at least in part. The target search image size was not reported for historical surveys, but we suspected it was larger than our minimum target search image size of 50 mm for timed swims. Alternatively, the smaller size distribution in 2016 was also consistent with both a fishery effect and a sea otter effect. Of these two options, an otter effect was far more likely because fishing pressure was assumed to be low in this area. Commercial fishing has been closed

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since 1995 and subsistence and personal use fishing pressure in this area was probably light to nonexistent due to its remoteness from Craig and Hydaburg, the nearest and most populous communities. The proportional shift toward larger sizes from 1980–1981 to 1986 was somewhat unexpected because the peak commercial catch (Southeast-wide) occurred from 1979–1981, and the local population was presumably fished down [in size and density] further from 1982 to 1985. Although this may have been a methodological difference, we suspect that it was real because the relative density declined dramatically within the same time period, and the proportional shift in length frequencies may simply have been growth of the remaining population in concert with recruitment levels too low to compensate.

One of the benefits of transects oriented perpendicular to the depth contour was that we were able to evaluate abalone density and size structure as a function of depth. We found no evidence for juveniles disproportionately occupying deeper habitats relative to adults as Sloan and Breen (1988) did, or any stratification of abalone size by depth in general. This may have been because juveniles were under rocks or so well hidden in crevices that our search methods were not effective for finding them. We did not include an invasive search component to this study because of the substantial amount of extra time that would have been required, but it would be a useful method to incorporate in future studies to address this question, as well as to assess true absolute density.

Length data is valuable in and of itself, but age data is even more valuable with respect to the amount of information that can be gleaned from a population. Historical age-length data for abalone populations in Southeast Alaska (Shepherd et al. 2000) permitted conversion of the lengths obtained in this study to estimated ages. The application of age-length keys from historical data (from 1998) to our dataset required assumptions of similar growth rates in the years preceding each data collection, as well as similar age-length relationships between historical vs. modern study locations. We believe the latter assumption is reasonable, given the small distances between Shepherd et al.'s (2000) Ridge Island study site to our Meares Pass study site, and their Gravina Island study site to our Gravina Island study site. We were less certain about the assumption of similar growth rates between time periods. Ocean conditions in the Northeast Pacific have been changing relatively rapidly in the last 20 years, which may have affected growth directly (e.g., via temperature or pH changes) or indirectly (e.g., via food quantity and/or quality, harmful algal blooms), as has been observed in recent years with abalone populations in California. Furthermore, the community structure in the Meares Pass area has undoubtedly shifted to a more algae-dominated state since the 1990s, as a result of the indirect effects of sea otter recolonization and associated grazer population reduction. No such transition has occurred at the Gravina Island study area, however, so growth rates there would have been expected to change less. Although beyond the scope of this study, at a future date we plan to use the estimated age data from this study, our recent study in Sitka Sound, and historical data to perform catch curve analysis and estimate the total mortality rates for modern and historical abalone populations in Southeast Alaska.

Density

The incorporation of complementary relative and absolute density estimation methods in this study allowed comparisons in space between our two study areas (relative and absolute density),

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and Sitka (relative and absolute density), as well as comparisons between present and historical data for Meares Pass (relative density only). Near-simultaneous data collection of relative and absolute density permitted a method comparison, which was important for insight into how to interpret relative density data and to assess the potential value of relative density estimates from historical data. There are important limitations and caveats for timed swims (e.g., McShane 1998), most notably the potential lack of repeatability due to among-observer differences. However, comparisons to historical relative density data would not have been possible in this study otherwise, and we mitigated within-year among-observer variability by restricting the data collector to a single person (TDW). We could not control for among-year among-observer variability, because all observers from previous surveys were retired and therefore not available to dive during our survey. We were cognizant of the limitations of the timed swim method but employed it anyway in order to investigate whether large differences existed between extant and historical relative density estimates. We limited our interpretation to large differences only because we deemed it unlikely that among-observer variability or minor differences in methods could account for such differences.

The primary advantage of a relative density survey was that it was more efficient than an absolute density survey, while the primary disadvantage was that it was not as repeatable. Relative density surveys for abalone have often taken the form of timed searches. Although this method is simple and efficient, there are problematic issues with their implementation (e.g., McGarvey et al. 2008). The most notable issue is high among-observer variability, which may indicate apparent differences among sites when there are actually none. Among-observer variability would probably have been significant in the present study because most of the observers had limited abalone surveys experience and search speed would have been difficult to standardize among observers. Search speed would have been influenced by a diver's search ability, experience with abalone surveys and/or harvesting, and complexity of substrate and vegetation type/cover. Rigorous among-observer calibration would have mitigated this issue to some extent, but the additional time required for such a calibration was not feasible with the limited amount of survey time available. To avoid this problem entirely, we employed one of the two most skilled abalone survey divers to conduct all timed search dives in both study areas. There were two primary risks to this approach. One of the risks was that data comparability would have been compromised if unforeseen circumstances arose and the chosen survey diver could not complete all timed search dives. Second, and arguably the more important risk, was that the chosen observer's search effectiveness was significantly higher or lower than the effectiveness of historical observers, which would have led to a consistent bias in comparison of results between historical and new data. This effect could certainly also have occurred with multiple observers, but it was more likely with a single observer. Having only one observer has several advantages; in particular it 1) replicates the historical surveys in which most dives were conducted by a single observer, 2) eliminates the risk of double-counting if there is more than one observer, and 3) eliminates having to coordinate and communicate search speed and direction underwater. The benefits and risks of this method and our preferred approach were carefully weighted, and given the limitation of resources, we ultimately decided that the method was worthwhile and that the single observer approach outweighed the introduction of potentially

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significant among-observer variability. Furthermore, the single-observer approach eliminated the need to train each diver with two methods (timed search and quadrat/transect).

Absolute density transects were oriented perpendicularly to ensure sampling coverage across the depth zone in which the majority of abalone typically occur in Southeast Alaska (personal observation). Consideration was given to orienting transects parallel to shore along prevailing depth contours as in other studies (Rothaus et al. 2008, Bell et al. *in prep*); however, assumptions would be required to choose appropriate depth contours, and additional time would be needed to establish multiple transects across depths per sample site to ensure adequate representation across the depth range. Another advantage of using perpendicular transects is that they are the standard method for other benthic invertebrate surveys conducted by ADF&G (red sea urchins, sea cucumbers, geoducks), which has proven to be an efficient sampling strategy.

The number of 1x4 m² quadrats per transect was limited to 30 because abalone surveys are often a very time-consuming process (~1–2 minutes/m², personal observation). Abalone are cryptic and difficult to see *in situ* because of their small size, effective camouflage, and behavior (e.g., slow movements, proclivity for hiding), especially when in complex habitat (e.g., substrate type, number of crevices, vertical relief, algal cover). In most cases, limiting sampling effort to 30 m² per diver should make it possible to complete one transect in a single dive, which will permit greater spatial coverage (more index sites) within a study area. The search image target size of ≥ 30 mm was different than that used for the relative density survey because the majority of abalone observed during 2015 Sitka Sound abalone survey work were < 50 mm. In the event of steep slopes in which the quadrat will not remain in place due to gravity, divers will assist each other by holding the quadrat in place while the other diver surveys. This protocol will ensure unbiased samples with respect to depth, but will result in unequal spacing of quadrats along the length of the transect because the slope of the seafloor is rarely constant. Ultimately, we decided that it was more important to sample in an unbiased fashion across depth, both because it is the axis of greatest variability in abalone density, and because we did not want to under-sample important abalone micro-habitats where depth changes rapidly (e.g., large boulders, bedrock ledges and drop-offs).

In the case of both relative and absolute density estimates, the data were highly skewed, which posed challenges for data analysis. Relative density data were highly skewed at the spatial scale of sites within study areas. Absolute density data were highly skewed at the spatial scale of 1 m² quadrats (the highest resolution sampling unit), 1x4 m² quadrats within sites (4 aggregated 1 m² quadrats at each transect depth increment), and sites within study areas. There were many zero counts for individual 1 m² quadrats, as expected, which is why we intended for the 1x4 m² quadrats to be the primary subsample unit within transects. In both cases (relative and absolute density datasets), this asymmetry forced us to use less powerful non-parametric tests instead of the intended more powerful parametric tests in order to test hypotheses. Data transformations (e.g., $\ln(x) + 1$) were attempted but the diagnostic results were not substantively different and the assumptions were still violated, so for simplicity the raw data were used in all analyses. Furthermore, the original intent was to compare means, but the non-parametric tests that we used instead required a comparison of median values. In future studies, it would be worth considering increasing the sample unit size for each method (for transects/quadrats, especially) to reduce this

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problem, although it would come with tradeoffs (e.g., ability to survey less sites) if total survey time was not increased accordingly.

It was unexpected that there was no significant relationship between absolute and relative densities at the same sites. Because of the relatively small sample size, we expected the data to exhibit relatively high variability and therefore statistical power to be relatively low, but the lack of any apparent relationship at all was surprising. This may have been due in part to not focusing sampling on the same depth zone; divers were forced to systematically sample the 0–9.1 m depth range during transect sampling, whereas the timed swim diver was under no such obligation and could spend their entire dive in shallower water with typically higher abalone densities. An alternative explanation is that abalone were aggregated at such fine spatial scales that the likelihood of a transect bisecting the most dense aggregations at a site was relatively low, but the timed swim diver could cover more area within the optimal depth range of abalone and home in on dense aggregations if they existed at a site. Another possible reason for the lack of correlation was that abalone were disturbed by the first divers to survey a given site (which could have been either transect divers or timed swim divers), and hid in refugia. Furthermore, transects required a swim-over with a meter tape prior to surveying, and then positioning the quadrat frame prior to searching for abalone. When the timed swim was done at a site first, the observer had the benefit of the element of surprise, and may have found and measured abalone before they had a chance to hide. It would be worth exploring different options for summarizing absolute density data in the future. For example, the absolute density could be calculated as the mean density of the top 50% of 1x4 m² quadrats within a transect, because quadrats in deeper water often had a very low densities, which diluted the leverage of any high-density transects in shallower, more optimal abalone habitat.