POPULATION DYNAMICS, GENETIC ANALYSIS AND MANAGEMENT TECHNIQUES FOR THE RECREATIONAL RED ABALONE (*HALIOTIS RUFESCENS)* FISHERY IN OREGON

by

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THESIS ABSTRACT

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Increased concern for changing population dynamics in abalone fisheries has necessitated shifts in conservation and management. Whole genome sequencing (WGS) results indicate that red abalone (*Haliotis rufescens*) in Oregon are genetically connected to population strongholds. Principal Components Analysis (PCA) of *H. rufescens* genetic samples showed considerable overlap across four Oregon sites. Larval dispersal potential and rare hydrodynamic regime shifts could sustain a small population. The red abalone in Oregon is imperiled and its future is uncertain, requiring increased conservation and monitoring efforts. This conservation and management plan suggests focusing on understanding ecosystem shifts driving population levels. Future considerations for managing such a marine broadcast spawning invertebrate with low densities, limited dispersal, and variable recruitment that hold historical, social, and economic value are considered and explored as climate shifts are expected to affect ecological parameters at the local and population level.

This thesis includes both previously published/unpublished and co-authored material.

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The data analyzed and presented in this chapter was collected and assimilated by a number of contributors, including Dr. Andrew Whitehead, Dr. Joanna Griffiths, and Scott Groth. Dr Whitehead and Dr. Griffiths contributed substantially to the genetics portion of this work, through the California Conservation Genomics Project, these authors assembled a newly annotated red abalone genome, performed DNA extraction and sequencing, and provided genetic samples for comparison. I was the primary contributor to the acquisition of genetic samples in Oregon, performed a principal components analysis of the genetics data, developed the PCA plots, contextualized the findings and did all the writing. Scott Groth contributed substantially to the historic data acquired from the Oregon Department of Fish and Wildlife, providing access to historic documents and red abalone recreational fishery data. I was the primary contributor to assembling the timeline of historic data and analyzing trends in management through time.

A. Introduction

Red abalone (*Haliotis rufescens* originally described by William John Swainson in 1822 Swainson, 1822), are marine mollusks from the class Gastropoda (subclass Prosobranchia, order Archaeogastropoda, family Haliotidae). Abalone have important roles in both nearshore ecology and fisheries, as herbivorous grazers on marine kelps and the target of commercial and recreational fisheries worldwide. Understanding the biology and ecology of abalone species in their local environment is necessary, as an integral component of the marine food web in temperate kelp forests, while also holding historical value. As broadcast spawners with short pelagic larval durations (PLDs), successful reproduction depends on close proximity of aggregated individuals (Button, 2008; Crofts, 1937; Oba, 1964; Tegner and Butler, 1989). Red abalone eat marine kelps and may compete with a host of species for space in nearshore waters including sea urchin species which also graze on kelp. Red abalone are the largest species of abalone, growing to sizes of up to 318 mm (Groth and Smith, 2022). Predators of the juvenile red abalone include octopus, fishes, and crab; however, adults may only face the sea otter as a natural predator (Hines and Pearse, 1982; Watson, 2000). The species ranges from Coos Bay, OR to Baja California, Mexico (Cox, 1962; Geiger, 1999), living in the rocky, shallow, vegetated nearshore areas. The red abalone population along the west coast of North America is patchily distributed where highly specialized environmental conditions are suitable (de Wit and Palumbi, 2013; Gruenthal et al., 2007). Population densities are highest in the central portion of their range in California; however, red abalone are found sparsely in Oregon, the northern termination of their biogeographic range limit (Groth and Gregory, 2018; Groth and Smith, 2022). Genetic connectivity of red abalone has been described as 'connected' in portions of their range (de Wit and Palumbi, 2013; Gruenthal et al., 2007); however, I present new information regarding connectivity through inclusion of red abalone genetic samples from Oregon.

Red abalone in Oregon live outside the highest concentrations of the central population, requiring an adaptative management approach that is focused on particular components of their biology. Population structure, size and stability of sedentary invertebrates, such as the red abalone, are determined by effective larval dispersal and local hydrodynamics (Cecino and Treml, 2021; Mccormick et al., 2012; Mikaye et al., 2017). As an important fishery species with a history of population collapse, effective red abalone management must integrate adaptive strategies to ensure maintenance of a stable population (Hobday et al., 2000; Tegner et al., 1996). In Oregon, a small recreational red abalone fishery occurred from 1950-2018, when it was closed due to low population levels (Groth and Gregory, 2018). The population dynamics of red abalone in Oregon are not well understood; however, attempts to elucidate population-level specifics have been completed through governmental agency-led surveys. Quantitative surveys have been performed periodically by the Oregon Department of Fish and Wildlife (ODFW) document very low densities (0.03 abalone/m^2 in 2015) that fall far below thresholds required to maintain populations (0.2-0.15 abalone/m^2, Shepherd and Partington, 1995). This thesis seeks to inform present and future Oregon red abalone managers through synthesis of biological, ecological, and historic information, coupled with new genetic data and implications for adaptive management of a rare and cryptic species.

i. Biology

The life history parameters of red abalone limit their ability to achieve consistent reproduction and consequently, stable populations. Red abalone are long-lived, slow growing, sedentary, and have delayed sexual maturity (Ault, 1985; Ault and Demartini, 1987; Geibel et al., 2010; Rogers-Bennett et al., 2007). The early life-history processes affecting spawning, larval development, dispersal, and settlement are not well understood. Adults are dioecious broadcast spawners that release gametes directly into the water column where they are fertilized (Ault, 1985; Boolootian and Giese, 1962; Carlisle, 1962; Price, 1974). Red abalone require dense aggregations for fertilization success (Button, 2008; Levitan, 1991). At low densities abalone may be subject to the Allee effect (Allee, 1931) which can diminish sperm viability when reproductive adults are not located within one meter (m) of each other, resulting in poor fertilization success and rapid population decline (Babcock and Keesing, 1999; Levitan, 1991; Levitan et al., 1992). Although red abalone can produce large numbers of eggs and sperm, fluctuations in food availability, ocean temperatures and local environmental conditions can diminish fecundity (Jiao et al., 2010; Rogers-Bennett et al., 2021, 2010). Following fertilization, a short-lived lecithotrophic larva may disperse for 5-14 days, with decreasing viability around 10 days (Searcy-Bernal, 1999). Local hydrodynamic conditions and species-specific ecology determine larval dispersal of abalones. Three modes of abalones' larval dispersal have been suggested: short-distance, long-distance and dual dispersal (includes periods of both short-distance and long-distance dispersal) (Mikaye et al., 2017). Biological factors also influence dispersal method, including spawning, pelagic larval duration (PLD), buoyancy and pre-settlement mortality (Bashevkin et al., 2020; Mikaye et al., 2017). Evaluation of biological factors coupled with dispersal method can elucidate connections between clustered sedentary marine invertebrates.

ii. Ecology

Changing environmental conditions and oceanographic processes have effects on the reproduction and recruitment of marine benthic invertebrates (Brierley and Kingsford, 2009; Gobler and Baumann, 2016; Hauri et al., 2009; Leighton, 1974). Bull kelp (*Nereocystis leutkeana)* is a primary food source of red abalone in Oregon. Following marine heat wave (MHW) events of 2014-2015, kelp bed densities throughout the US West Coast declined (Rogers-Bennett et al., 2021; Rogers-Bennett and Catton, 2019). Red abalone are in direct competition with sea urchins for food and space. Both red sea urchins (*Mesocentrotus franciscanus*) and purple sea urchins (*Strongylocentrotus purpuratus*) can live for long periods of time without consistent food and have more flexible diets than red abalone (Rogers-Bennett and Catton, 2019; Tegner and Levin, 1982). In addition to competition for food and space, increased frequency of ocean warming events can negatively impact the reproductive success of red abalone (Hart et al., 2020; Kawana et al., 2019; Rogers-Bennett et al., 2010). Increases in sea surface temperature (SST), decreases in ocean pH and changes in salinity can alter gamete release, vertical migration, and reproductive viability (Zippay and Hofmann, 2010). Rising sea surface temperatures could shorten pelagic larval duration (PLD) which could impact genetic connectivity within populations (Bashevkin et al., 2020). Increased frequency of El Niño/Southern Oscillation (ENSO) climate events can also have deleterious effects on red abalone populations, by depressing the thermocline, diminishing the California Current (CC), and reducing upwelling (Boch et al., 2017).

Throughout the west coast of North America, red abalone populations have recently suffered a collapse due to a combination of environmental factors, fishing pressure, and their difficulty in maintaining a reproductively stable population. Although this species of abalone has been found to be highly fecund and can exhibit long-distance dispersal, it does not recruit reliably and most often larvae travel only short distances. As the frequency of ocean warming events increases, fluctuations in food availability, salinity variability, and decreases in pH will continue to affect the larval dispersal and influence population dynamics of red abalone.

iii. Population Genetics

Broadcast spawning marine invertebrates with lecithotrophic larvae and short larval durations, such as red abalone, typically have low potential for gene flow (de Wit and Palumbi, 2013; Hamm and Burton, 2000). Despite this, red abalone populations throughout California are genetically connected, indicating that this species can exhibit long-distance dispersal, despite normally exhibiting short-distance dispersal over an increasing spatial gradient (Gruenthal et al., 2007). However, information about genetic connectivity is currently lacking for red abalone in Oregon, where fragmented populations occur at the northern terminus of their biogeographic range. Local selective pressures including variable SST, pH, wave action, predator presence and food availability would likely induce genetic differentiation between these regional populations (Sanford and Kelly, 2011). Allele frequency changes through time, due to genetic diversity and variance within a population (Lynch et al., 1995; Robertson, 1965). As Oregon red abalone populations continue to decline, it is important to understand and evaluate the genetic connections within and between clusters to determine goals for conservation and management. Genetic analysis of red abalone individuals in Oregon when compared to northern California would allow for preliminary determination of population dynamics through assessments of genetic diversity and structure. For example, strong genetic structure would indicate isolated metapopulations (Miller et al., 2014), guiding management frameworks to focus on applying metapopulation theory to these specific groups within Oregon.

Future red abalone management and conservation decisions should take into account knowledge of genetic populations in Oregon, increasing understanding of red abalone larval behavior under changing conditions, evaluating stock assessment, sampling and management techniques for rare and cryptic species, and monitoring of environmental effects on populations.

B. Methods

i. Historic Data

Historic data and information about red abalone in Oregon was evaluated through a review of literature and data contained in ODFW unpublished reports, conversations, fishery data, and density/abundance survey results. Limited peer-reviewed literature is available detailing the presence and biology of red abalone in Oregon. Consequently, supplemental data from ODFW unpublished reports was combined with conversations with fishery participants and managers as important sources for this effort. Data included information from historical recreational permits and exploratory commercial catch data, which was not previously catalogued electronically. Unpublished reports drafted by ODFW personnel were reviewed for information regarding the history of red abalone in Oregon acquired through communication with Oregon's red abalone fishery managers.

a. ODFW Population Surveys

ODFW has conducted periodic surveys for red abalone in Oregon, with qualitative surveys being performed from the 1950s-1980s, with limited application to management. Quantitative surveys were conducted first in 2011 at two sites in southern coastal Oregon where red abalone habitat and presence was known to occur, and surveys were repeated in 2019 and 2022. Results from these surveys, both quantitative and qualitative, provided data for this report and information to develop the subsequent conservation and fishery management plan for red abalone in Oregon.

ii. Larval Dispersal

A literature search was conducted in the Web of Science database using the following search criteria by topic: "abalone" AND "larval development" NOT "polychaeta"; "abalone" AND "larval dispersal" NOT "polychaeta". Due to the overlap of shell-boring polychaetes during abalone development, which was not the focus of this study, search was further narrowed as not to include articles that focused on boring polychaete development. Search results were confined to the topic of 'Marine Biology' as categorized by the database. Relevant results focused on larval duration and dispersal methods of abalone species worldwide. Literature was searched in the Web of Science database using search terms: "*Haliotis rufescens*" AND "larval development" NOT "polychaeta". Relevant results were reviewed categorize specifics of development and dispersal methods.

iii. Genetics

To examine the population genetics of red abalone in Oregon, I collected new samples of red abalone tissue from four locations throughout their range along the Oregon coast. I collaborated with colleagues from UC Davis to develop a Principal Components Analysis (PCA) comparing red abalone samples from 205 individuals collected from 18 sites in Oregon and California. Collection methods in the field, laboratory methods of DNA extraction, sequencing, and analysis methods are described below.

a. Field Methods

Genetic clips of red abalone tissue were collected at four sites in Oregon, in the rare areas where they are found: Cape Arago, Nellie's Cove, Rogue Reed, Samuel Boardman State Park (Figure 1). Sites were selected based on 1) known presence of red abalone, 2) accessibility, 3) geographic separation, and 4) low probability of sampling transplanted individuals. I used agency knowledge combined with information from fishery (pers. Comm. Tim Foley and Scott Groth) and academic sources (Golden and Langdon, 1995; Nielsen, 1967), to identify sites. Sites were difficult to access; methods included intertidal search, snorkel search and searches conducted by commercial divers. Sites were separated by rocky headlands and were a minimum of 20 km (12 miles) apart. Since transplantations of red abalone have occurred in the recent past (Golden and Langdon, 1995; Nielsen, 1967), I heavily relied on unpublished agency documentation to target sites where the lowest probability of transplantation occurred. Samples collected at 14 sites in California were utilized for comparison from 144 individuals, with five sites in central California (1998-2021) from 45 individuals, nine sites in northern California (1999-2011) from 99 individuals.

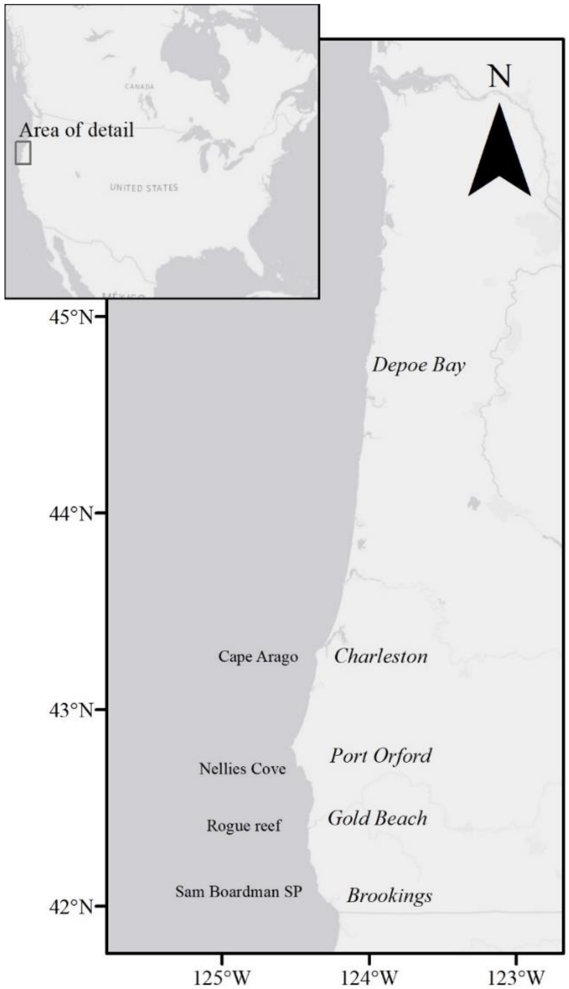

Figure 1: Map of genetic sampling locations for red abalone (*Haliotis rufescens*) collected in 2021 in Oregon.

Genetic clips of red abalone were collected from Oregon sites in 2008-2009 (21 individuals) and 2021 (40 individuals), for a total of 61 individuals. In 2008-2009, samples were collected in a cooperative effort between ODFW and participants of the recreational abalone fishery. I organized the collection of the Oregon samples in 2021, which were collected from four sites (Figure 1). Red abalone were removed from substrate using abalone irons to minimize damage to their foot and brought to the surface. Abalone were measured (shell length (SL) and weight). Samples from 3-6 epipodial tentacles were removed with sterilized tweezers and dissecting scissors, and placed into a vial with 95% EtOH, following protocol outlined by California Department of Fish and Wildlife (CDFW, Ian Taniguchi). All red abalone sampled in 2021 were returned to the water to minimize any damage to individuals.

a. Lab Methods

DNA from red abalone samples was extracted at the University of California, Davis (Department of Environmental Toxicology; Whitehead Lab, Davis, California) and sequenced at the University of California, Berkeley (QB3 Genomics Facility). Dr. Joanna Griffiths extracted DNA using Agencourt Ampure XP beads consistent with methodology from Ali et al., 2017. Re-extraction was performed using Qiagen DNeasy Blood and Tissue kit (Hilden, Germany). Whole genome sequencing (WGS) was performed through paired-end sequencing (2x150 bp), utilizing whole-genome libraries constructed using NEBNext Ultra DNA Library Prep kit (Illumina) for 205 samples. A bioanalyzer was used to assess concentration and fragment size, followed by sequencing with 10x coverage across six lanes total with a NovaSeq S4. All DNA prep, extraction and sequencing was performed through collaboration with UC Davis by Dr. Griffiths.

b. Analysis Methods

Red abalone DNA sequencing was successful, and results were analyzed and interpreted using Principal Components Analysis (PCA) plots. Using the R package ggplot2 and adapting a previously developed pipeline (McGirr, 2018), I constructed PCA plots comparing: 1) Oregon samples to northern and central California samples, 2) Oregon samples at four sites, and 3) two decades of samples collected from Oregon.

iv. Management Techniques

I reviewed literature focused on abalone (*Haliotis spp.*) fisheries management to understand the strengths and weaknesses of different regulatory strategies and categorized temporal trends. A literature search using the Web of Science database was conducted with the following search criteria: "*Haliotis*" AND "management". Search results were confined to 'Marine Biology' and 'Fisheries' as defined by the database to further filter relevant results. Management strategies were categorized based on details of strategy, grouped together by similar techniques for comparison of trends. Results from the search were separated into seven categories: 1) adaptive management, 2) anthropogenic consideration, 3) biological, 4) length/age, 5) precautionary management, 6) reserve/closure, and 7) spatial/ecosystem management. Adaptive management entails strategies designed to be altered and re-evaluated based on success or environmental shifts. Anthropogenic consideration refers to management strategies that focus on fishery participant actions. Biological refers to management that incorporates biological estimates including egg-per-recruit, yield-per-recruit models and/or spawning potential. Length/age refers to strategies that set limits based on a minimum size limit (i.e., Minimum Legal Size (MLS)) or age-at-maturity model. Precautionary management refers to strategies that take action prior to population declines or negative environmental shifts. Reserve/closure entails strategies that utilize closed areas or reserves as refugia for sensitive life history stages. Spatial/ecosystem management refers to strategies that utilize effects of species interactions or manage abalone as part of the ecosystem over a larger spatial scale. In addition, I participated in California's recent discussions of the Red Abalone Management Strategy Evaluation Working group and interviewed managers (Scott Groth and Steven Rumrill) at ODFW for further context of regional management strategies.

C. Results

i. Historic Data

Red abalone were first documented in Oregon in the early 1900s, and have been used by tribal, commercial, and recreational sectors, increasing in value, and requiring more understanding and management. Agency publications detail the beginning of the recreational red abalone fishery in Oregon (Snow, 1959). However, many supplemental resources that were not peer-reviewed or publicly available including letters, report drafts, and commission hearing reports, were utilized and catalogued for future review and use. Physical copies of letters and documents from 1953-1995 written by ODFW, formerly Oregon Fish Commission (OFC), personnel were reviewed and scanned by this author and utilized in the first peer-reviewed publication for history and management of abalone in Oregon (Groth and Smith, 2022). Details of these resources are described in the document review synthesis section below. Data sources from recreational catch rates, exploratory commercial work, and permitting are described in the reported data section below.

a. Document Review Synthesis

Beginning in 1952, Lowell Marriage, (aquatic biologist for the Oregon Fish Commission (OFC)) wrote a letter addressing the presence and abundance of abalone in Oregon to an interested colleague in California[1]. The contents of the letter reported the rarity and lack of surveys for abalone in Oregon, with the intent to conduct departmental surveys in the following summer of 1953 and collect additional data from Oregon universities that might have more information about abalone presence and abundance. In the same year (1952), a response from

[1] Marriage 1952, Table 1.

University of Oregon (UO) Professor Bayard McConnaughey was written to Lowell Marriage detailing his familiarity with abalone presence in Oregon due to student findings and reports at the Oregon Institute of Marine Biology (OIMB), indicating presence of red abalone in Coos Bay at least as early as 1926[2]. Professor McConnaughey reported that in 1926, an unpublished student report detailed the finding of *Haliotis rufescens* at Qochyax Island (formerly Squaw Island), as well as being listed on a "1926 Collection List: Final List". A 1953 report draft by James McCauley of the molluscan resources of Oregon's outer coast details the habitat and presence of abalone in Oregon, particularly that red abalone taken are large (10-11-inch (254-279 mm) SL), but rarely found; summarizing that abalone are not present in large numbers in Oregon, and fishing regulations should follow California's guidelines[3]. A 1954 letter from Lowell Marriage further confirms these accounts, stating that large red abalone are found in southern Oregon in small numbers[4]. The first official report of abalone surveys (qualitative) was written in 1955 by McCauley and Marriage and reports that red abalone are not considered an important species in Oregon due to their paucity, and lack of consistent and reliable information regarding their presence and biology[5]. A noticeable shift occurs in 1959, with the first rules of the fishery being suggested and adopted for recreational take. OFC aquatic biologist Dale Snow reports the first biological information regarding red abalone in Oregon in an unpublished draft report utilizing California reports and harvest control rules (HCRs) as guidelines for Oregon regulations[6]. Snow suggests setting the minimum legal size (MLS) at 8 inches (203 mm), instead of the California size of 7 inches (178 mm), and taking a conservative approach to the resource, due to low levels of individuals and lack of information regarding their populations in Oregon. A

[2] McConnaughey 1952, Table 1.
[3] James McCauley 1953, Table 1.
[4] Marriage 1954, Table 1.
[5] McCauley and Marriage 1955, Table 1.
[6] Snow 1959, Table 1.

report draft in 1962 by Dale Snow further elucidated the work done by the OFC to determine more information about the red abalone resource in Oregon[7]. Specifically, the OFC contracted divers to assess the population through timed dives between 1958-1962, concluding that a commercial fishery would not be possible due to the lack of individuals found during surveys. Snow also reported that the sex ratio of male to female red abalone through gonad examination was 1:1, and that very few (6) juveniles (2-5 mm SL) or sublegal (< 8 inches; 203 mm SL) red abalone were found during surveys[8]. Snow (1962) provided the first quantification of biology and population patterns for red abalone in Oregon (Table 1).

A second shift in Oregon red abalone management began in the 1960s, with concerns surrounding their abundance and sustainability of harvest with a heavier focus on enhancement efforts and increased monitoring that persisted through the 1990s. This shift towards data-focused management from the 1960s-1990s included two outplanting projects, first in 1967-1974, and the second planned for 1994-1999, as well as the introduction of a harvest permit in 1972 to acquire fishery dependent data.

In 1967, a new fishing opportunity for red abalone was suggested through outplanting of juveniles to an area north of their historical range in Whale Cove, Depoe Bay. Red abalone were thought to be restricted from range expansion north of Coos Bay due to a 50 mile (80 km) stretch of sandy habitat[9]. Results of the initial outplanting were reported by Gaumer (1975), stating that 5,660 juvenile red abalone (5-20 mm SL) acquired from a shellfish hatchery in northern California were placed in Whale Cove throughout 1967. Intertidal surveys to count individuals,

[7] Snow 1962, Table 1.
[8] Snow 1962, Table 1.
[9] Nielsen 1967, Table 1.

monitor growth and survival were conducted annually[10]. Growth estimates for red abalone in Oregon are sparse; however, Gaumer 1975 reported that Laimons Osis utilized growth data from Whale Cove monitoring to estimate an average of 22 years for red abalone to grow to the MLS of 8 inches (203 mm SL) in Oregon. In addition to juveniles placed in Whale Cove in 1967, a total of 277 adult red abalone were placed in Whale Cove between 1968-1974. Annual surveys to tag and recapture red abalone in Whale Cove were performed from 1968-1991, then sporadically from 1992-2018.

A second planned outplanting project was attempted as a collaboration between ODFW and Oregon State University (OSU), with the goal to develop red abalone rearing methods for locally adapted individuals[11]. Difficulties with using hatchery-reared red abalone, coupled with loss of momentum for the project halted outplanting efforts, resulting in the historic termination of official outplanting and breeding projects in Oregon.

Modern management actions (2000-2018) shifted towards increased quantitative monitoring with a heavier focus on increased biological and ecological understanding and active management in response to low densities and unfavorable environmental conditions. These actions ultimately culminated with the close of the recreational fishery until specific biological and abundance information could be acquired to establish new management techniques in Oregon (Groth and Gregory, 2018; Rumrill, 2021).

[10] Gaumer 1975, Table 1.
[11] Richmond and Schaefer, 1995; Langdon and Golden, 1995, Table 1.

Table 1: Unpublished Oregon Department of Fish and Wildlife (ODFW) documents detailing the history of red abalone (*Haliotis rufescens*) in Oregon 1952-1995.

Year	Author (s)	Type	Title
1952	Marriage, Lowell D.	Letter	N/A
1952	McConnaughey, Bayard	Letter	N/A
1953	McCauley, James E.	Report Draft	The Mussel, Piddock, and Abalone Resources of Oregon's Outer Coast
1954	Marriage, Lowell D.	Letter	N/A
1955	McCauley, James E. Marriage, Lowell D.	Report	The Intertidal Mussel, Piddock, and Abalone Resources of Oregon's Outer Coast
1959	Snow, Dale C.	Commission Report	Suggested Personal-Use Regulations for Red Abalone (Haliotis rufescens) in Oregon
1962	Snow, Dale C.	Report Draft	Abalone Research Studies 1958-1962
1967	Nielsen, Jack	Commission Hearing Report	Whale Cove Shellfish Regulations for Fish Commission Public Hearing
1972	Fish Commission of Oregon	Commission Hearing Report	Staff request for a permit system to harvest red abalone
1975	Gaumer, T.	Report Draft	Whale Cove Abalone
1975	Reimers, Paul	Memo	Rare and Endangered Species
1978	Lukas, Jerald	Report Draft	Abalone Research and Management Activities, 1958-77
1995	Richmond, Neil Schaefer, John	Research Proposal	A Proposal for a Red Abalone Enhancement Trial in Oregon

Table 1

(continued).

Year	Author (s)	Type	Title
1995	Langdon, Chris Golden, James	Research Proposal	Development of a red abalone broodstock from abalone native to Oregon

b. Reported Data

Sources of red abalone data available from ODFW documents include both fishery independent and fishery dependent data spanning years 1958-2022.

Fishery independent data includes: 1) qualitative surveys from the 1950s-1960s, 2) pilot surveys performed in 2011, and 3) index surveys in 2015, 2019 and 2022. An exploratory commercial survey effort lasted from 1958-1962, aimed at determining if population levels could support a commercial red abalone fishery. Data from this effort includes: 1) habitat descriptions and 2) red abalone measurements (Snow, 1962). Pilot surveys were performed in 2011 to test methods for red abalone abundance quantification, comparing polygonal index sites to timed surveys (Groth, 2011). Data from this effort includes: 1) shell length (SL) measurements and 2) count per hour density measurements. Index surveys were first performed in 2015 at two sites selected for their importance to the fishery (Port Orford and Brookings), repeated at one site (Port Orford) in 2019 and planned for 2022-2023 at both sites (Groth and Smith, 2022; Rumrill and Groth, 2016; pers. Comm. Scott Groth 2022). Trends in abundance and size distributions are difficult to quantify using available data, due to differences in methodology used through time; however, comparing timed survey data from 1969 and 2011 shows higher detection in recent surveys, which could be attributed to increased diver expertise (Chapter II; Table 5). Densities from index surveys in 2015, 2019 and preliminary surveys in 2022 show low densities, trending downward (Chapter II; Table 6).

Fishery dependent data is available through catch report permits, which were required for fishery participants from 1973-1979 and 1996-2017. Data from permits includes: 1) catch data and 2) permittee information. Participation in the recreational fishery increased with time, with an average of 126 permits issued from 1973-1979, increasing to 175 permits from 1996-2017 (Chapter II; Figure 15). The peak of fishery participation was in 2017 with 280 issued permits, just before the fishery closure in 2018. As participation increased, annual average catch increased from 28 red abalone (1973-1979) to 145 (1996-2017), peaking at 299 red abalone caught in 2017 (Chapter II; Figure 16). The fishery is also categorized as a primarily SCUBA (Self-Contained Underwater Breathing Apparatus) and trophy fishery, with 51.4% of participants SCUBA diving, and a mean fishery size of 245 mm SL (Chapter II; Figure 13). Alternative methods for red abalone catch in Oregon are free dive (29.3% of users) and shore pick (19.2% of users).

ii. Larval Dispersal

Abalone larvae literature search utilizing search terms “abalone” AND “larval development”, confined to ‘Marine Biology’ returned 114 results, spanning years 1972-2022, covering 16 distinct species, two hybrids, and four subspecies. Due to the overlap of shell-boring polychaetes during abalone development, which was not the focus of this study, search was further narrowed to “abalone” AND “larval development” NOT “polychaeta”, returning 102 results. From 102 results, 52 articles reported abalone larval duration times and were reviewed for this study, giving 56 total larval duration times, due to some articles focusing on multiple abalone species (Table 2). Abalone larval dispersal literature search utilizing terms “abalone” AND “larval dispersal” returned 57 results, spanning years 1991-2021. Larval development and dispersal of abalone varies by species and location; influenced and limited by biological adaptation and hydrodynamic effects. Each abalone species has developed unique biological adaptations to succeed in their local environment. A total of 32 articles denoted a type of suggested dispersal pattern for abalone, specific to the target species of study (Table 3). Dispersal was categorized as “Localized/Limited” when dispersal was suggested to be only localized to a specific area, “Adaptive/Variable” when dispersal was found to be variable or adaptive based on biological or ecological conditions, and “Long-distance” when dispersal was suggested to be over long-distances in relation to previous studies (Figure 2).

Table 2: Publications reviewed for estimated pelagic larval duration (PLD) among abalone (*Haliotis spp*.). *Indicates subspecies; **Indicates hybrid.

Publication	Species/Subspecies/Hybrid	Larval Duration (days)
Sawatpeera 2001	*Haliotis asinina*	1-3
Jackson 2005	*Haliotis asinina*	2-4
Williams 2008	*Haliotis asinina*	3-4
Williams 2009a	*Haliotis asinina*	3-4
Williams 2009b	*Haliotis asinina*	4-10
Stewart 2011	*Haliotis asinina*	4-6
Jackson 2011	*Haliotis asinina*	2-6
Bautista-Teruel 2013	*Haliotis asinina*	1-4
Moss 1999	*Haliotis australis*	5-10
Wong 2010	*Haliotis coccoradiata*	4-5
Gao 2016	*Haliotis discus*	3-7
Sasaki and Shepherd 1995	*Haliotis discus hannai* *	4
Kawamura 2001	*Haliotis discus hannai**	5
Takami 2003	*Haliotis discus hannai**	3-4
Fukazawa 2005	*Haliotis discus hannai**	5
Takami 2006	*Haliotis discus hannai**	3
Guo 2015	*Haliotis discus hannai**	3
Onitsuka 2018	*Haliotis discus hannai**	3
Li 2019	*Haliotis discus hannai**	1-2
Guo 2020	*Haliotis discus hannai**	1-2

Table 2. (continued).

Publication	Species/Subspecies/Hybrid	Larval Duration (days)
Koyama 2020	*Haliotis discus hannai**	3-5
Zhao 2004	*Haliotis discus hannai x Haliotis discus discus***	2-4
Guo 2015	*Haliotis diversicolor*	3
Wang 2016	*Haliotis diversicolor*	3
Lu 2004	*Haliotis diversicolor*	2-3
Stott 2004	*Haliotis diversicolor aquatilis **	2-3
Zhang 2008	*Haliotis diversicolor supertexta **	2
Zhang 2010	*Haliotis diversicolor supertexta**	6
Moran 2003	*Haliotis fulgens*	7
Alter 2017	*Haliotis fulgens*	3-4
Moss 1992	*Haliotis iris*	5-9
Phillips 2006	*Haliotis iris*	3-10
Page 2006	*Haliotis kamtschatkana*	9
Crim 2011	*Haliotis kamtschatkana*	8
Timmins-Schiffman 2013	*Haliotis kamtschatkana*	4
Grubert 2004	*Haliotis laevigata*	3-10
Balkhair 2016	*Haliotis mariae*	2
Mzozo 2021	*Haliotis midae*	3-5
Garland 1985	*Haliotis rubra*	6-8
Grubert 2004	*Haliotis rubra*	3-11
Alter 2017	*Haliotis rubra*	3-4
Spaulding and Morse 1991	*Haliotis rufescens*	9
Slattery 1992	*Haliotis rufescens*	6-7
Degnan and Degnan 1995	*Haliotis rufescens*	3-7
Shilling 1996	*Haliotis rufescens*	6-9
Degnan 1997	*Haliotis rufescens*	9
Vavra 1999	*Haliotis rufescens*	8
Zippay 2010	*Haliotis rufescens*	6-14
Swezey 2020	*Haliotis rufescens*	7
Lafarga-De la Cruz 2013	*Haliotis rufescens x Haliotis discus hannai***	6
Leighton 1972	*Haliotis sorenseni*	9-10
Hobday 2001	*Haliotis sorenseni*	9-10
Moran 2003	*Haliotis sorenseni*	7-10
McCormick 2016	*Haliotis sorenseni*	5-8
de Viscose 2007	*Haliotis tuberculata*	2-4
Wessel 2018	*Haliotis tuberculata*	5

Table 3: Publications reviewed for larval dispersal method, categorized as Localized/Limited, Adaptive/Variable, or Long-distance by abalone species (*Haliotis spp*.). *Indicates publication denotes multiple species.

Year	Author(s)	Species	Dispersal Method
1991	McShane and Smith	*Haliotis rubra*	Localized/Limited
1992	Shepherd and Partington	*Haliotis laevigata*	Adaptive/Variable
1993	Tegner, M*	*Haliotis fulgens*	Localized/Limited
1993	Tegner, M	*Haliotis corrugata*	Localized/Limited
1995	Sasaki and Shepherd*	*Haliotis discus hannai*	Adaptive/Variable
1995	Sasaki and Shepherd	*Haliotis scalaris*	Adaptive/Variable
1999	Stevenson and Melville	*Haliotis cyclobates*	Adaptive/Variable
2001	Roberts, RD, and Lapworth	*Haliotis iris*	Adaptive/Variable
2001	Tegner et al	*Haliotis rufescens*	Adaptive/Variable
2002	Takami et al	*Haliotis discus hannai*	Long-distance
2002	Hobday and Tegner	*Haliotis rufescens*	Adaptive/Variable
2004	Grubert, MA*	*Haliotis rubra*	Adaptive/Variable
2004	Grubert, MA	*Haliotis laevigata*	Adaptive/Variable
2004	Day, R	*Haliotis rubra*	Adaptive/Variable
2006	Stephens, SA	*Haliotis iris*	Adaptive/Variable
2006	Miner, CM	*Haliotis cracherodii*	Localized/Limited
2008	Saunders, TM	*Haliotis rubra*	Localized/Limited
2008	McCormick et al	*Haliotis sorenseni*	Long-distance
2009	Miller	*Haliotis rubra*	Localized/Limited
2009	Saunders, T	*Haliotis rubra*	Localized/Limited
2010	Watson, JR	*Haliotis rufescens*	Adaptive/Variable
2010	Mikaye, Y	*Haliotis discus hannai*	Adaptive/Variable
2011	Mikaye, Y	*Haliotis discus hannai*	Adaptive/Variable
2012	Jackson, DJ	*Haliotis asinina*	Adaptive/Variable
2012	McCormick et al	*Haliotis rufescens*	Long-distance
2013	Rossetto, M*	*Haliotis fulgens*	Localized/Limited
2013	Rossetto, M	*Haliotis corrugata*	Localized/Limited
2016	Rogers-Bennett, L	*Haliotis rufescens*	Localized/Limited
2017	Alter, K*	*Haliotis laevigata*	Adaptive/Variable
2017	Alter, K	*Haliotis rubra*	Adaptive/Variable
2017	Pena, TS	*Haliotis rufescens*	Adaptive/Variable
2018	Ortega-Cisneros, K	*Haliotis midae*	Adaptive/Variable
2018	Neuman, MJ	*Haliotis kamtschatkana*	Localized/Limited
2021	McCarroll, RJ	*Haliotis midae*	Adaptive/Variable

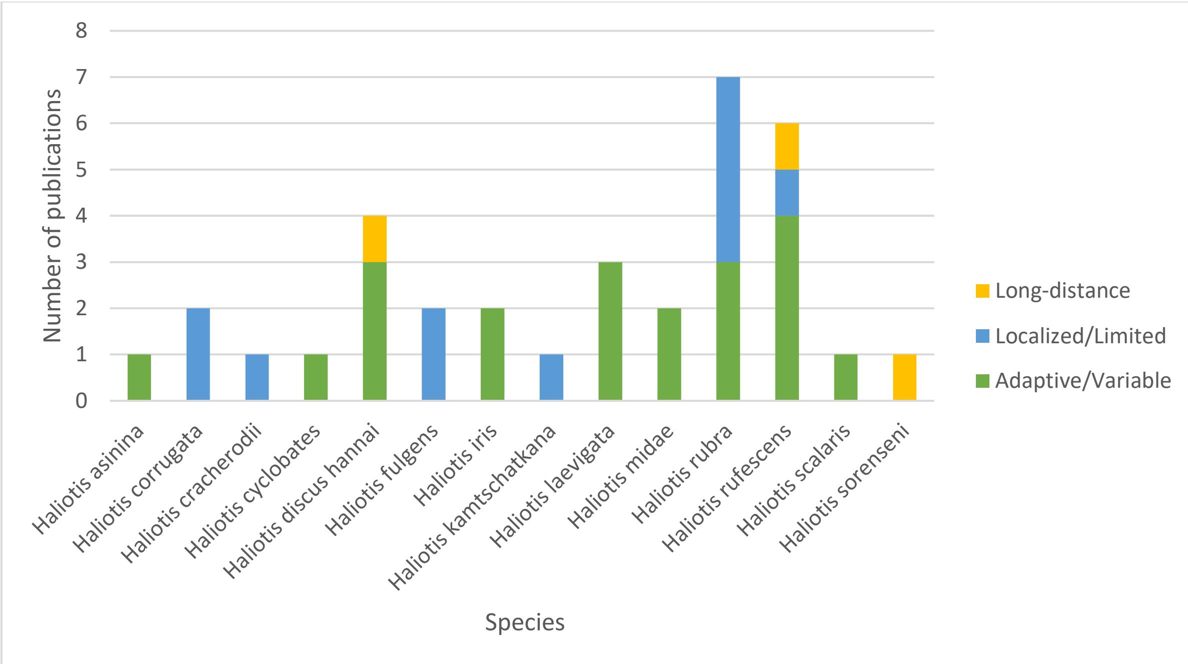

Figure 2: Larval dispersal method of abalone (*Haliotis* spp.) species reported by reviewed publications (n=42).

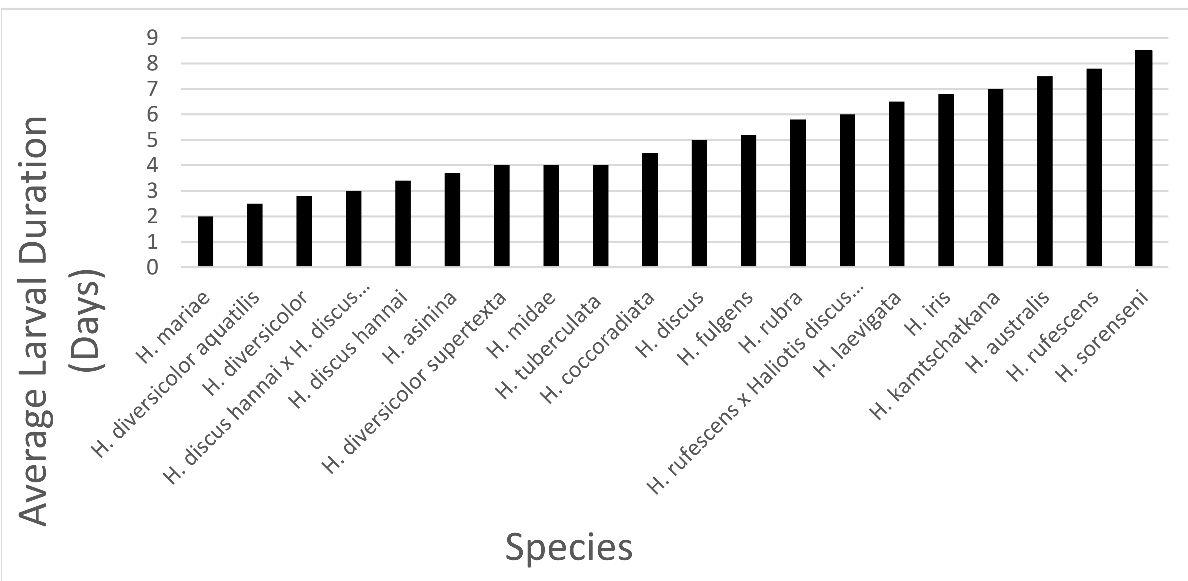

Figure 3: Average Pelagic Larval Duration (PLD) of abalone (*Haliotis* spp.) by species from reviewed publications (n=56). Range: 2-8 days; mean: 4-6 days.

a. Larval Literature Review Synthesis

Abalones' larval behavior, including dispersal method, competency period and reaction to environmental conditions vary by species and location. Larval behavior and environmental reaction affect settlement success and population structure. Two distinct stages are involved in settlement that dictate how larvae will develop and settle: 1) metamorphosis, in which specific anatomical and physiological changes occur and 2) settlement, marked by behavioral changes that orient larvae. Prior to settlement, larvae grow until they reach a period of competence, marked by development of anatomical structures that allow larvae to sense their environment and determine settlement cues. In red abalone, competency to complete metamorphosis is marked by the development of eyespots, cephalic tentacles, and a muscular foot, which occurs 6-7 days following initial larval development (Mccormick et al., 2012; Slattery, 1992). Cephalic tentacles have chemosensory abilities through development of tubules and sense environmental cues using associated chemical signals: (1) γ-aminobutyric acid (GABA)-mimetic peptides present on the surfaces of crustose coralline algae, (2) mucus secreted by juvenile conspecific abalone, and (3) diamino acids dissolved in seawater, indicating ideal oceanic pH (Degnan and Morse, 1995; Morse et al., 1979; Slattery, 1992). Red abalone are competent and ready to settle when they sense the appropriate environmental conditions through the fourth tubule on their cephalic tentacles. Settlement induction through specific chemical cues is an adaptation allowing red abalone larvae to detect ideal habitat. Ideal habitat based on these chemical cues would be presence of other red abalone that have successfully settled, indicating sufficient nutrition, physiological conditions, and potential for reproductive success.

Storms, physical barriers, and thermal shifts can impact settlement requiring potentially adaptive traits including variable pelagic larval duration (PLD). Red abalone larvae have a PLD of 5-14 days, the longest reported PLD maximum extent for all abalone species worldwide. However, the average PLD for red abalone is 7.8 days (Figure 3), shorter than the average PLD for the deep-living white abalone (*Haliotis sorensenii*) which has an average PLD of 8.5 days and both species can delay metamorphosis following hatching without suffering a decline in post-settlement juvenile survival (Mccormick et al., 2012; McCormick et al., 2008). Both red abalone and white abalone live along the west coast of North America, occupying habitats that may allow for increased dispersal through extended PLD. Comparing the mean PLD for abalone in North America to worldwide shows that North American abalone are, on average, in the plankton longer than species worldwide, potentially due to the lower latitudes of worldwide species, and higher associated average SST (Figure 4).

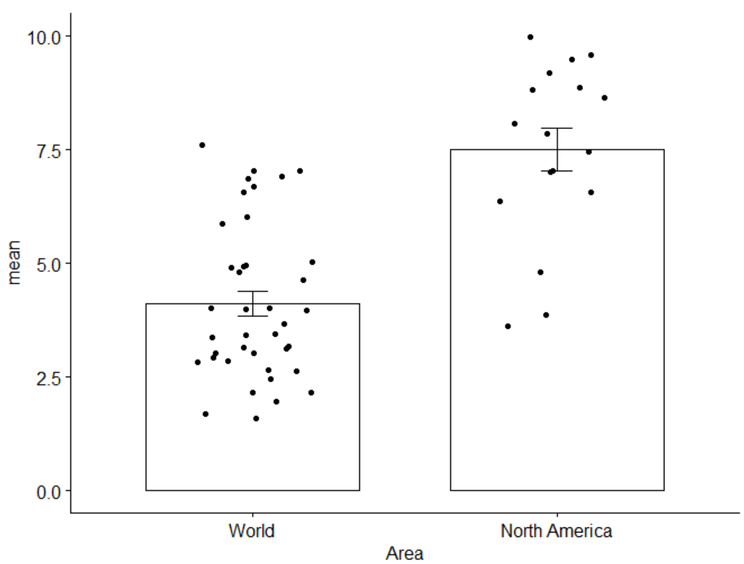

Figure 4: Average Pelagic Larval Duration (PLD) of abalone (*Haliotis spp.*) comparing North America with worldwide species from literature review 1999-2020 (n=56).

iii. Genetics

Genetic results demonstrate broad and general genetic connectivity between red abalone in southern Oregon and northern/central California. Visualization of the data through PCA plots confirms genetic connectivity but does not provide more specific quantification of allelic diversity and gene flow (Figure 2). The scree plot demonstrates percentage of variance explained by each Principal Component (PC), with PC 1 and 2 explaining 6.3% and 6.22% of variance respectively (Figure 5). Red abalone in central California and northern California show more variation between PC1 and PC2, suggesting higher genetic variation and diversity than Oregon red abalone, which are clustered tightly and centered within central and northern California samples (Figure 6). Removing outliers reveals more fine-scale patterns, further demonstrating Oregon samples nestled within northern and central California samples (Figure 7).

Four locations along the southern Oregon coast were sampled to identify potentially localized genetic differences. Results demonstrated minimal variation among sites within Oregon, with the most variation found in the Brookings samples (Figure 8). Within Oregon, two sampling efforts have taken place, a decade apart, first in 2008-2009, and again in 2021. The comparison between these two sampling events demonstrates slight differences in the red abalone in Oregon between decades, 2008 and 2021 (Figure 9).

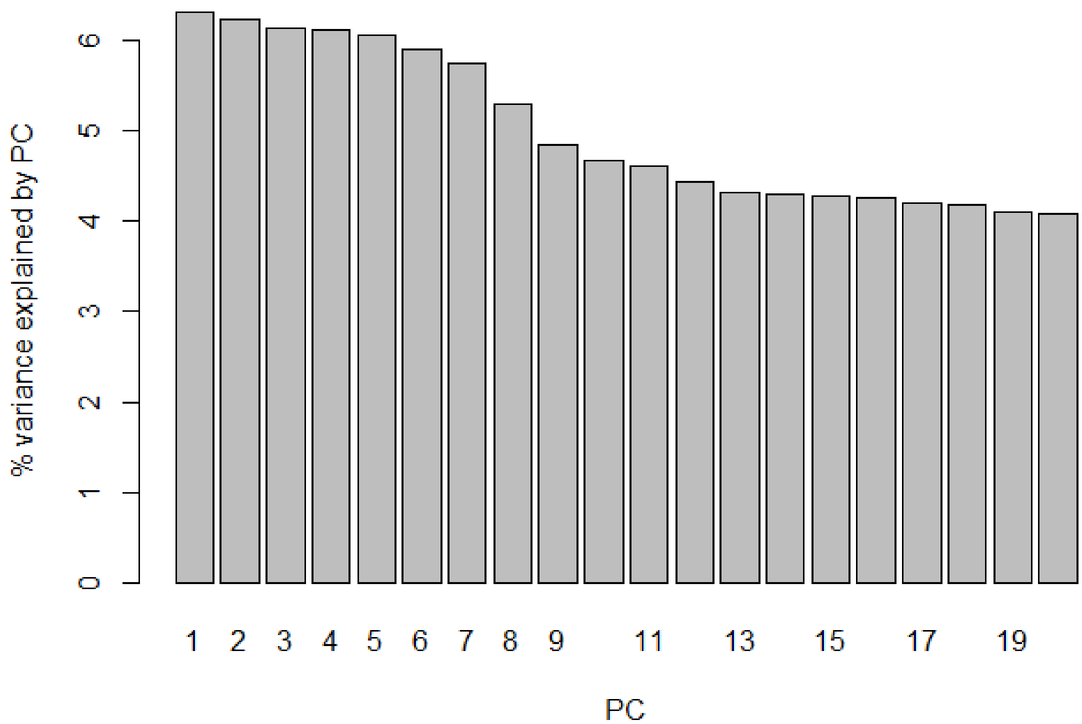

Figure 5: Scree plot displaying percent (%) variance by Principal Components (PC) comparing red abalone (*Haliotis rufescens*) collected from 1999-2021 at sites in California and Oregon.

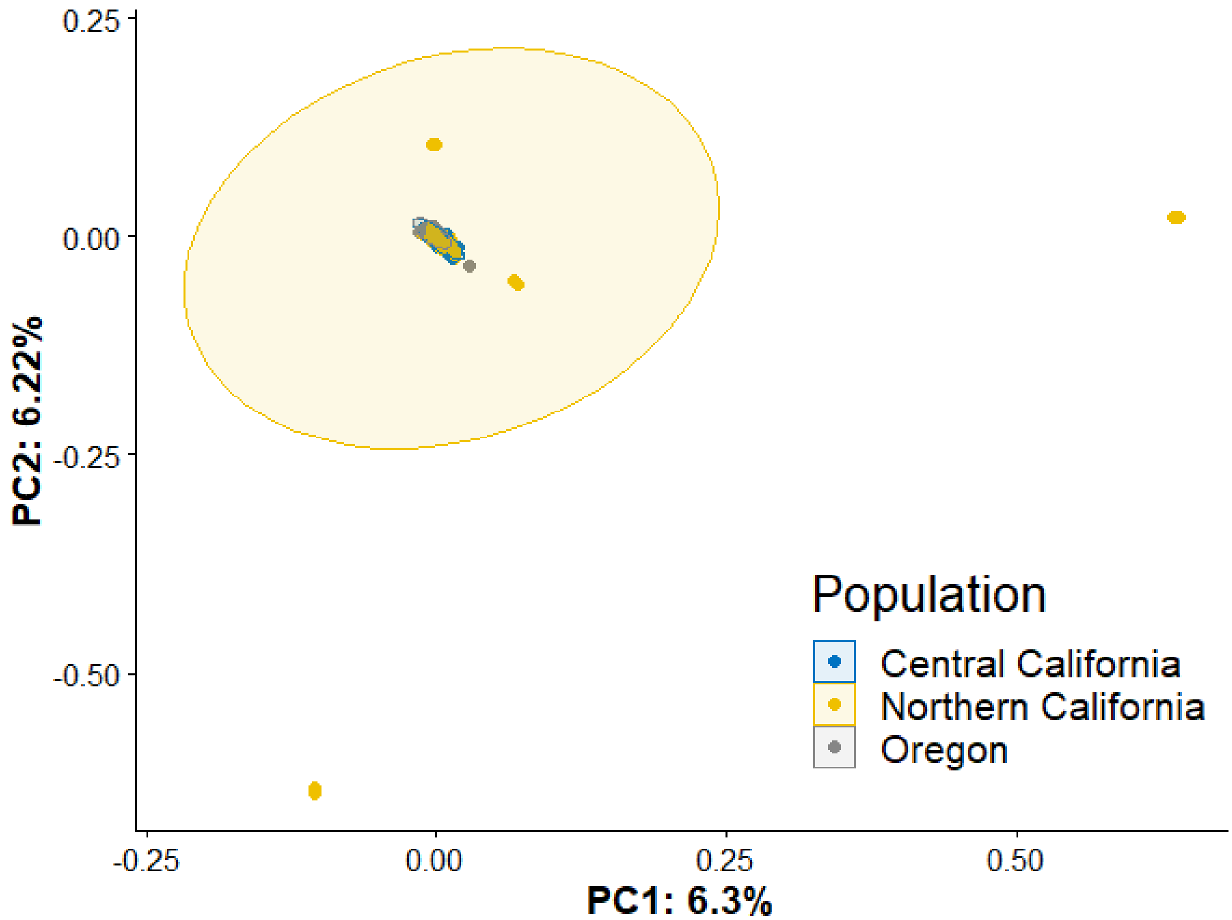

Figure 6: Principal Components Analysis (PCA) plot comparing red abalone (*Haliotis rufescens*) genetic samples collected in central California, northern California, and Oregon 1999-2021.

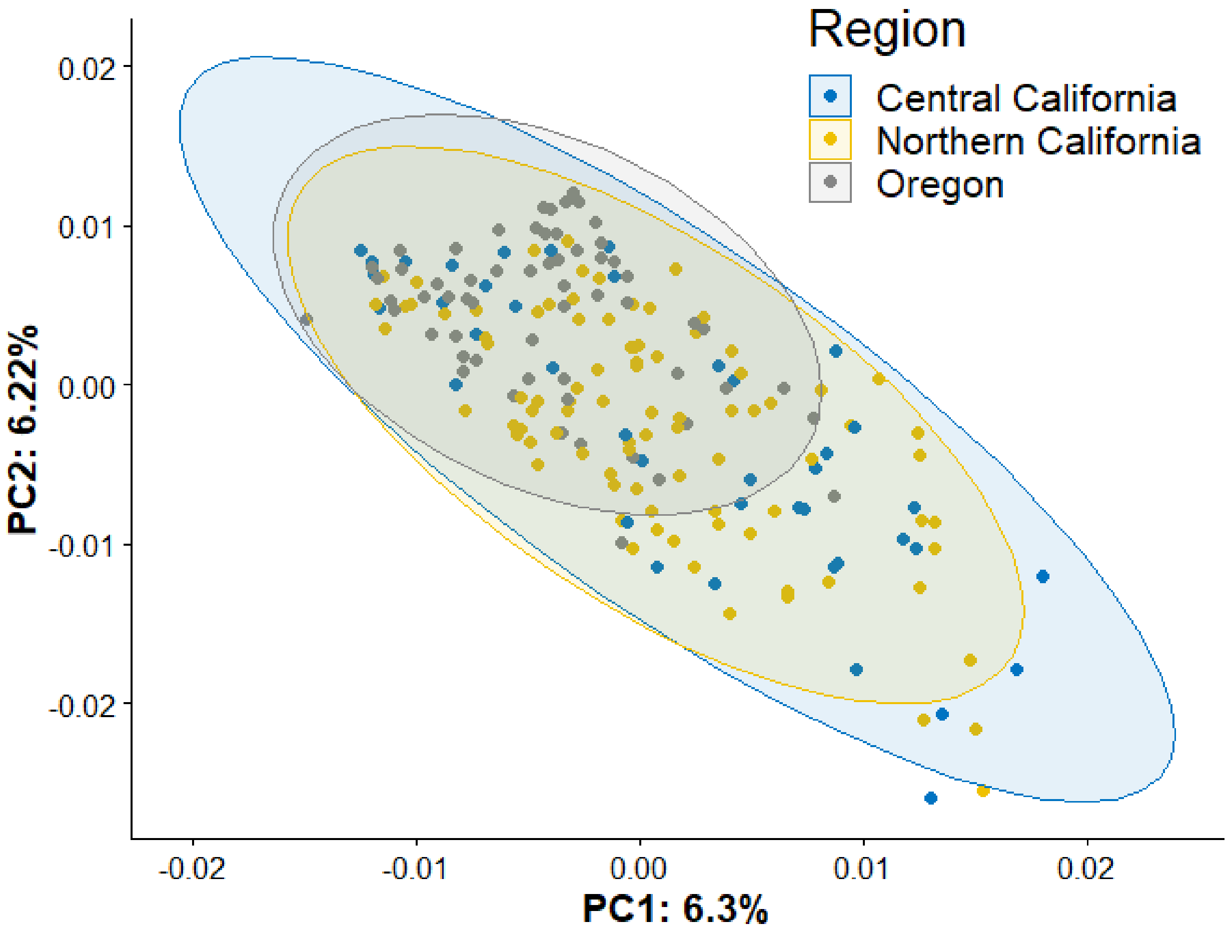

Figure 7: Principal Components Analysis (PCA) plot comparing red abalone (*Haliotis rufescens*) genetic samples collected in central California, northern California and Oregon from 1999-2021 with outliers removed.

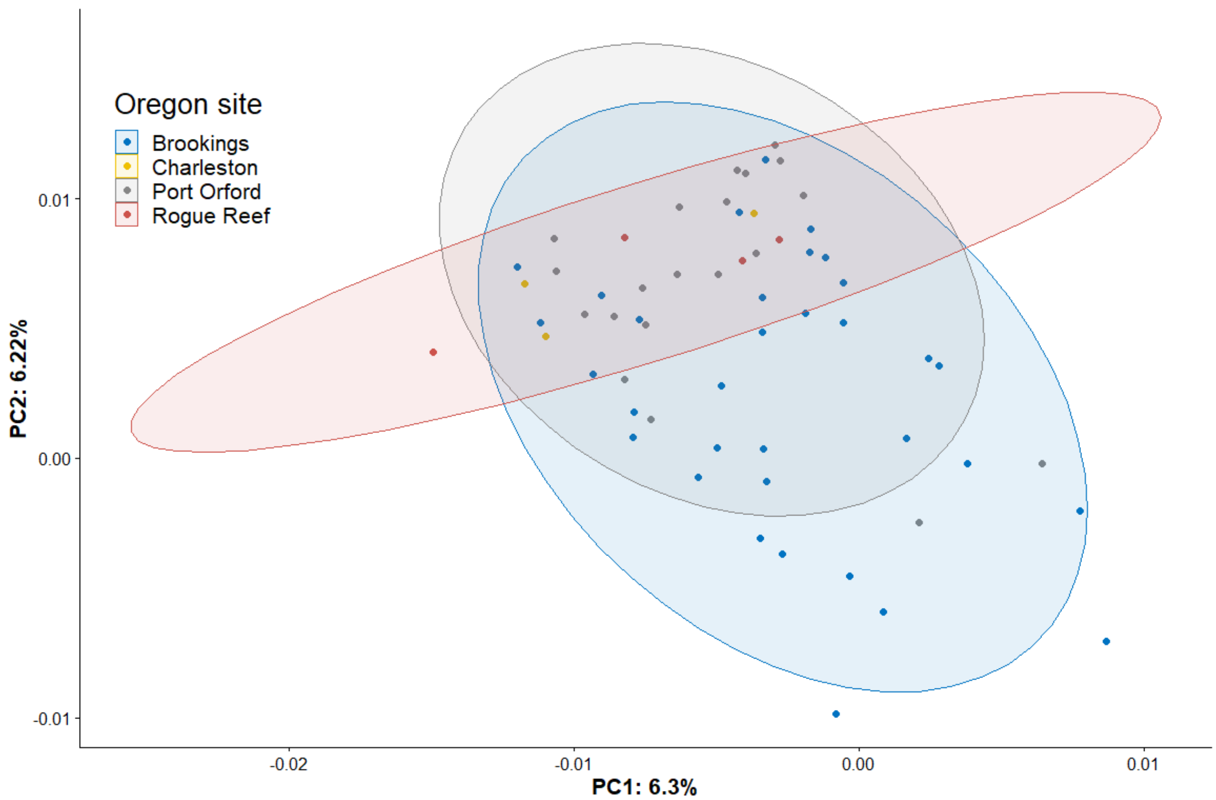

Figure 8: Principal Components Analysis (PCA) plot comparing red abalone (*Haliotis rufescens*) genetic samples collected in Oregon at four sites in 2008 and 2021 with outliers removed.

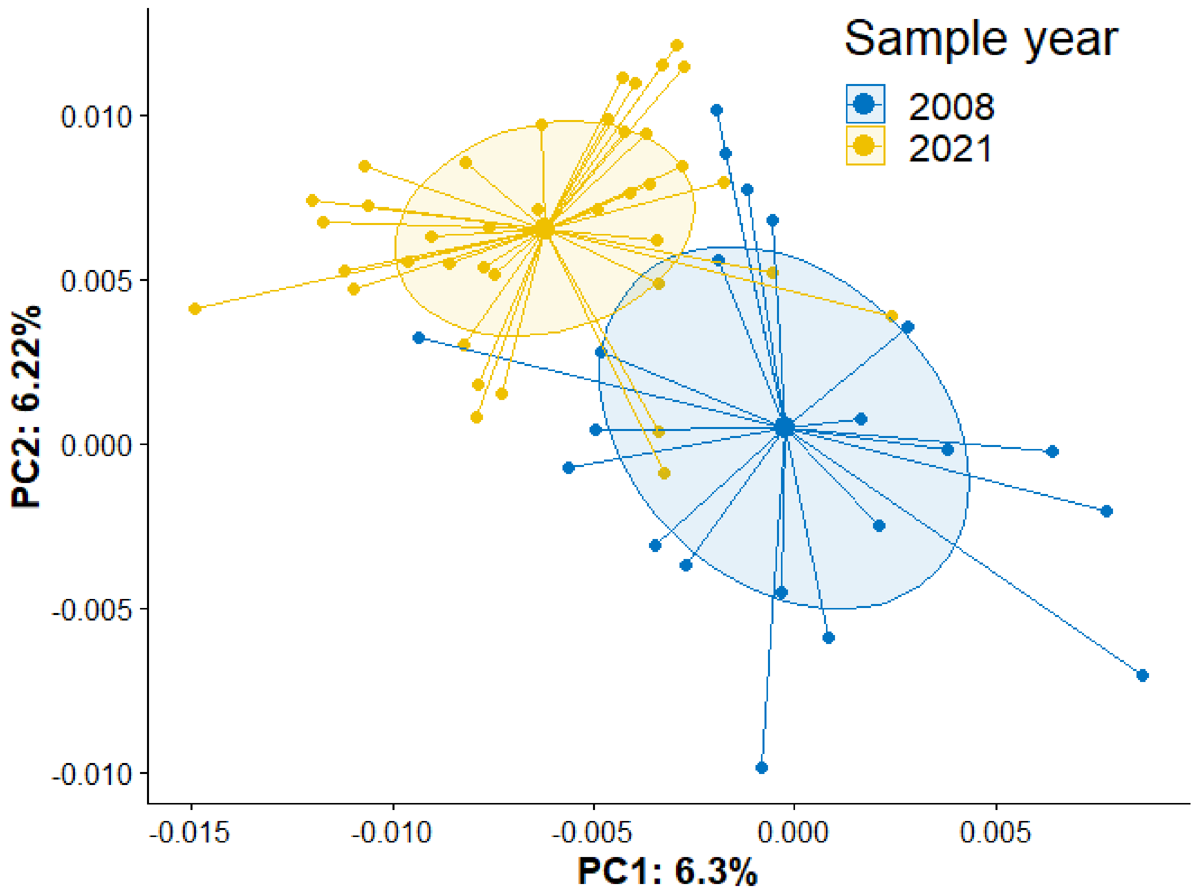

Figure 9: Principal Components Analysis (PCA) plot comparing red abalone (*Haliotis rufescens*) genetic samples collected in Brookings, OR in two sample years, 2008 and 2021.

iv. Management Techniques

Abalone fishery management techniques differ worldwide based on species, economic associations, and geography. A literature search performed using ISI Web of Science, utilizing search terms "*Haliotis*" AND "management", filtered through database topics 'Marine Biology' and 'Fisheries' returned 154 results, spanning years 1982-2022, covering 15 countries, focusing on 15 species, two subspecies and one hybrid. Following general review of 154 articles, results were further filtered to focus on wild abalone species and population-level management. Articles focused on aquaculture techniques, or abalone species that are not managed in the wild (i.e., hybrids) were excluded due to lack of relevance, resulting in 81 articles from nine countries and 15 distinct species that have been or are currently the target of managed fisheries. The countries or regions that have published literature on abalone fisheries management are Australia (33), the United States (21), New Zealand (10), South Africa (5), Mexico (4), Canada (3), the Philippines (1) and Chile (1) (Table 4).

Management strategies including survey methods, stock assessments, harvest control rules (HCRs), and biological parameters were evaluated for each article found in my literature search. Categories were separated into adaptive management, anthropogenic consideration, biological, length/age, precautionary management, reserve/closure, and spatial/ecosystem management. Overall, abalone fisheries worldwide utilize a combination of these strategies, which has evolved through time. Most commonly, length/age is utilized due to the importance of size at age and maturity for setting harvest sizes or minimum legal size (MLS) (Figure 10). Management of abalone fisheries worldwide has shifted towards a focus on ‘biological’ factors to set rules, incorporating these factors into spatial and ecosystem models (Table 4; Figure 10). Biological factors include egg-per-recruit models, larval dispersal methods, PLD, and genetics. Incorporation of climate change into management strategies for abalone fisheries is a rising consideration, with six articles focused on developing strategies to trigger closures, increase recovery efforts, and reduce fishing pressure with increased sea surface temperatures (SST) (Haaker 1998, Harley and Rogers-Bennett 2004, Rogers-Bennett et al. 2010, Plaganyi et al. 2011, Rogers-Bennett and Catton 2019, Velez-Arellano et al. 2020).

Table 4. Number of publications regarding abalone (*Haliotis spp*.) management strategies/dynamics I reviewed by region and species

REGION	PROVINCE/STATE	SPECIES	# OF PAPERS	YEARS
AUSTRALIA	SOUTH AUSTRALIA	*H. laevigata*	12	2001-2021
AUSTRALIA	VICTORIA, NEW SOUTH WALES, TASMANIA	*H. rubra*	24	1992-2022
AUSTRALIA	WESTERN AUSTRALIA	*H. roei*	4	2013-2018
CANADA	BRITISH COLUMBIA	*H. kamtschatkana*	3	2003-2017
CHILE		*H. discus hannai*	1	2017
JAPAN		*H. diversicolor*	1	2005
MEXICO		*H. fulgens*	3	2008-2020
MEXICO		*H. corrugata*	1	2010
NEW ZEALAND		*H. iris*	11	1982-2020
NEW ZEALAND		*H. australis*	1	2015
PHILIPPINES		*H. asinina*	3	2004-2019
SOUTH AFRICA		*H. midae*	10	2001-2021
UNITED STATES	CALIFORNIA	*H. rufescens*	12	1998-2019
UNITED STATES	CALIFORNIA	*H. corrugata*	2	1993-2013
UNITED STATES	CALIFORNIA	*H. cracherodii*	2	2004-2010

Table 4.

(continued).

REGION	PROVINCE/STATE	SPECIES	# OF PAPERS	YEARS
UNITED STATES	CALIFORNIA	*H. fulgens*	1	2013
UNITED STATES	WASHINGTON	*H. kamtschatkana*	1	2008
UNITED STATES	CALIFORNIA	*H. sorenseni*	3	1998-2013
UNITED STATES	**OREGON**	***H. rufescens***	**14* (*unpublished)**	**1953-1995**

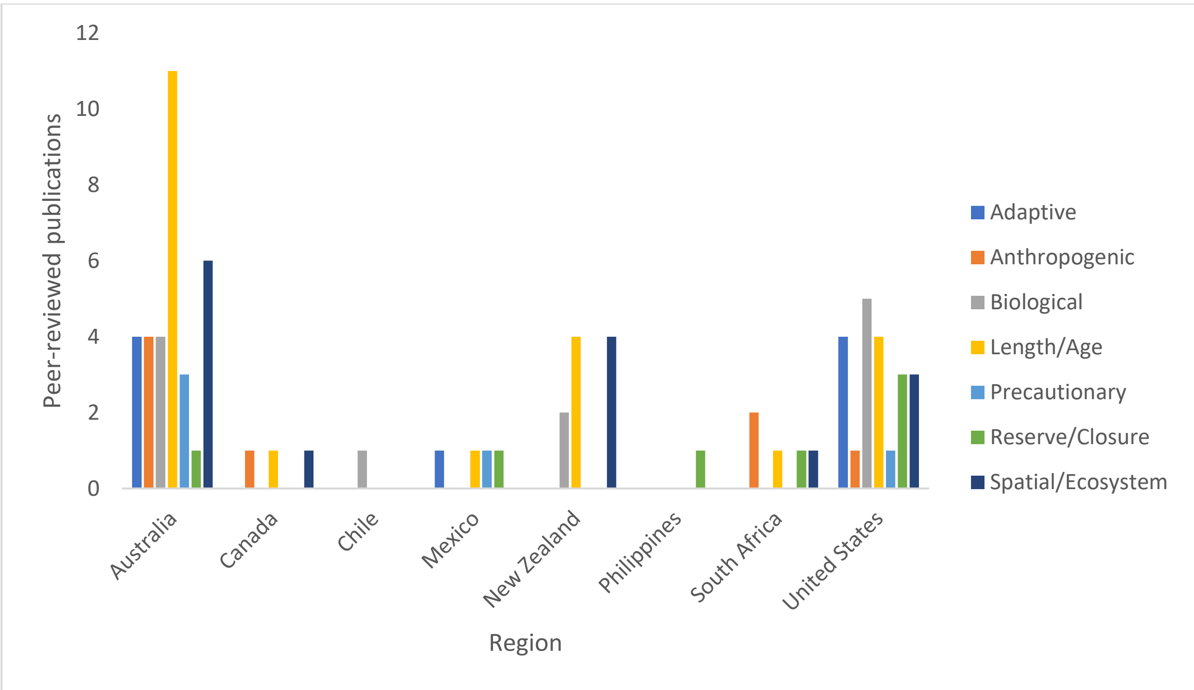

Figure 10: Abalone (*Haliotis spp*.) management techniques by region compared across seven categories.

D. Discussion

Oregon's red abalone population and fishery are a unique case study. When compared with management strategies and biological aspects of other abalone species, red abalone in Oregon exhibit differences in history, adaptation, and sustainability. Management of red abalone in Oregon has followed a similar pattern to worldwide abalone management trends. Beginning in the early 1950s, red abalone were found to be sparse in Oregon, and considered an insignificant resource in the state and not a valuable investment for biological understanding. In 1959, biological examination became more important as a recreational fishery and guidelines were established. Increased monitoring and biological assessments characterized the decades that followed, with the introduction of a catch report permit in the 1970s, and enhancement efforts that continued through the late 1990s intended to bolster a growing fishery. Although both monitoring and interest increased, the population and resources to evaluate biological parameters and abundance remained sparse. Oregon fishery managers relied on trends in adjacent California fisheries to inform concerns and evaluate harvest impacts. Each management action for Oregon's red abalone fishery has been recommended by agency biologists to be conservative and reactive, with internal communications from each era of the fishery detailing concerns about population levels and lack of information on abundance and distribution as well as paucity of juvenile presence. Quantification of red abalone abundance in Oregon began in 2015, utilizing monitoring strategies recommended by more robust abalone fisheries in Australia and California. These strategies, although effective for application in larger-scale abalone fisheries and populations, do not provide holistic understanding of the red abalone population in Oregon, situated at the species northern range extent.

Increased understanding of biological parameters that influence population structure, size and overall health can be useful tools to examine a small, patchy population such as Oregon's red abalone. Abalone are broadcast spawning marine invertebrates with varying reproductive adaptations, influenced by environmental and physiological limitations. Although most abalone species have a short PLD (average of 5 days), abalone species in North America had a longer PLD (average of 7 days), and larval dispersal was reported to be adaptive or variable depending on ocean temperature, currents, and settling conditions. These findings indicate that both larval duration in the planktonic environment and dispersal method are heavily influenced by temporal and annual fluctuations. Red abalone and white abalone (*H. sorenseni*) have the longest reported potential for long distance dispersal due to their increased duration of a competency period, intensified further when larvae develop in colder ocean temperatures found at deeper depths (*H. sorenseni* habitat) and more northern latitudes. A longer competency period increases potential for long-distance dispersal of larvae, which could also increase the spatial scale of abalones and explain genetic connectivity over long geographic distances. Previous genetic studies on red abalone connectivity indicate the potential for long-distance dispersal on rare occasions; however, this would not be sufficient to sustain a population and would result in extremely low densities and a truncated size distribution favoring mostly older, larger individuals. The genetic information acquired from this study suggests a homogeneous population of red abalone throughout Oregon to central California, demonstrating evidence of the exchange of genetic material between central California, northern California, and Oregon. Recruitment of red abalone in Oregon has not been quantified; however, agency biologists and fishery participants familiar with the species have observed that red abalone throughout Oregon are "ripe" year-round, suggesting lack of spawning (pers. Comm. Scott Groth). These findings suggest limited dispersal and variable recruitment, which can characterize the northern range limit of a broadcast spawning marine invertebrate population and indicate irregular population dynamics created through unique hydrodynamic factors.

Further considerations for interpreting the data acquired from this study include mechanistic approaches to evolutionary change through contextualization of dispersal, population dynamics, and acute thermal events. Recently, studies examining evolutionary changes through space rather than time have been applied to marine organisms with planktonic larvae due to differential dispersal and local genetic adaptation (Sanford and Kelly, 2011). Although the preliminary genetic data from this study suggests little divergence between northern and central California when compared to the Oregon population, differentiation at a local level is still possible. Traits can be locally adapted and divergent, evolving by differentially successful genes through space, categorized as “spatial sorting” (Shine et al., 2011). The application of spatial sorting and the drift paradox, in which sedentary adult populations persist against average oceanic currents (Byers and Pringle, 2006), to red abalone spatial dynamics can elucidate origins of a small, patchy population with variable recruitment events. Marine heat waves (MHWs) are increasing in duration and intensity, with repercussions for biological shifts and poleward migrations. Future studies investigating local adaptations to changing ocean conditions evident through allelic diversity could be valuable for further understanding of red abalone population origins and recruitment patterns at the northern extent of their range.

This study demonstrates trends in abalone management, details the history of management in Oregon, and contextualizes the unique biological and environmental parameters influencing the imperiled red abalone for application in management and population biology. Managing a species with low abundance, limited larval dispersal, and variable recruitment at the northern extent of their range requires precautionary ecosystem-level conservation and intervention. Management strategies incorporating changing climatic factors through improved stock assessments would be the most effective at conserving the red abalone in Oregon. Through a combination of biological factors including larval behavior, shifts in thermal and hydrodynamic patterns, prey and predator abundance changes, and genetic connections, an integrative approach to conservation and management could ensure the future of red abalone in Oregon.

II. CONSERVATION AND FISHERY MANAGEMENT PLAN FOR RED ABALONE IN OREGON

The framework and data presented in this chapter was completed through support and material provided by the Oregon Department of Fish and Wildlife (ODFW) and Scott Groth. The framework for this chapter including some specific wording regarding policies were provided by ODFW using the Marine Fisheries Management Plan (MFMP) and the Dungeness crab Fishery Management Plan. I adjusted the framework based on the recreational red abalone fishery needs and history and did all the writing. Scott Groth contributed immensely to the data provided in this chapter, including the commercial and recreational fishery data for red abalone in Oregon, and through the following publication:

Groth, S., Smith, K., 2022. Abalone in Oregon: Trends in populations and fisheries. Marine Fisheries Review. In press.

A. Introduction

i. Purpose and Need

Red abalone (*Haliotis rufescens*) are a key component of the marine intertidal and subtidal environment throughout the North American west coast. Like other abalone fisheries worldwide (Hobday et al., 2000; Karpov et al., 2000) the recreational red abalone fishery in Oregon is vulnerable to overexploitation and difficult to manage for sustainability. Abalone fisheries are particularly susceptible to depletion or collapse due to patchiness of populations, life history strategies that promote endemism and episodic recruitment, variability in reproductive output, and lack of resilience to environmental changes (Hobday et al., 2000). Red abalone populations are difficult to quantify due to both the paucity of individuals and cryptic behavior in Oregon. Red abalone are in high demand by recreational harvesters, throughout their range and as a global treasure prized for their large size, desirable meat, and beautiful shells. The high commercial, recreational and cultural value of red abalone necessitates development of a conservation and management strategy that is adaptive to changing conditions along the Oregon coast. Therefore, we address this management demand in a way to ensure a recreational fishery could exist without damaging the population in the future, with conservation goals in mind to promote and establish resilience in the current and future population.

The recreational red abalone fishery is managed at the state level by the Oregon Department of Fish and Wildlife (ODFW) / Marine Resources Program (MRP). Quantitative stock assessments and periodically consistent surveys are not employed. Instead, ODFW has historically managed this resource through an individual permitting system with a Minimum Legal Size (MLS), daily and annual limits. Interest in the recreational red abalone fishery in Oregon and harvest levels increased steadily over the past three decades until recent suspension of the fishery (2018-present). Identification of an effective management strategy is vital to maintain viability of red abalone populations in Oregon as a valued living resource for future enjoyment and use.

The recreational red abalone fishery in Oregon faces numerous threats posed by changing biological and environmental factors, including increased competition, predation, and regional shifts in environmental conditions. This Conservation and Fishery Management Plan for Red Abalone in Oregon (CFMP) describes these challenges and presents a series of recommendations and suggested tools designed to address the pressing management issues.

The purpose of the CFMP is to provide the overall framework for protection and maintenance of red abalone populations. The CFMP presents an assessment of the current state of knowledge about red abalone in Oregon marine waters, describes the historic and current management strategies that regulate harvest, and identifies recommendations for future conservation measures to enhance sustainability of this valuable living resource.

ii. Goals

The CFMP for Red Abalone in Oregon was developed to identify an integrated approach to management that evaluates the conservation status of red abalone populations in Oregon and explores the possibility to develop a minimal-impact (aka "*de minimis")* recreational fishery. The primary management goals of the CMFP are:

1. **Ecological** – Ensure the long-term reproductive capacity and natural dynamics of the red abalone population, minimize impacts to other species, and support ecosystem health.
2. **Social/cultural** – Promote diverse opportunities for present and future generations to harvest, use, or enjoy the red abalone resource.
3. **Economic** – Support the economic vitality of red abalone as a high-value target for a *de minimis* recreational fishery that provides multiple benefits to Oregon's coastal communities.

iii. Framework for Oregon Marine Fisheries Management Plans

The framework for Oregon Marine Fisheries Management Plans provides context and structure to guide development of species-specific Marine Fisheries Management Plans (MFMPs) that ensure orderly fisheries and equitable access to marine resources by different users, while maintaining ecological integrity (Oregon Department of Fish and Wildlife, 2015). The Framework outlines a consistent approach for MFMP development that includes a comprehensive evaluation of fishery resources and a detailed assessment of harvest management strategies. Specifically, the Framework identifies the information included in MFMPs to achieve the following goals:

1. Provide access to marine resources for present and future generations.
2. Minimize bycatch, incidental catch, and mortality related to fishery interactions with non-target marine organisms.
3. Coordinate the management of commercial and recreational fisheries.
4. Minimize complexity of management.
5. Consider the socioeconomic needs of local communities, including both consumptive and non-consumptive uses and values.
6. Involve the public in the fisheries management process.

iv. Major State Policies

Several overarching policies guide the management of marine fishery resources and development of fishery management plans in Oregon. These policies are thoroughly described in the MFMP Framework and are listed below:

- Food Fish Management Policy (1975; Oregon Revised Statute § 506.109)
- Wildlife Policy (1973; ORS § 496.012)
- Native Fish Conservation Policy (NFCP; 2003; Oregon Administrative Rule 635-007-0502 through OAR 635-007-0509)
- Oregon Nearshore Strategy (2015; ODFW, 2016)
- Oregon Territorial Sea Plan (1994; OPAC, 1994)
- Statewide planning goals (DLCD, 2010; OAR 660-015)

v. Document Organization

This CFMP for Red Abalone in Oregon is organized into two primary sections according to the Framework structure. Section B - Resource Analysis comprehensively describes the status of the red abalone resource in Oregon, including biological and ecological information, an analysis of stock status, factors affecting the species, and areas for future research. Section C -Management and Conservation Strategy articulates historical and current management practices, goals for the resource, issues facing the fishery, and appropriate management and conservation tools for the recreational red abalone fishery.

vi. Acronyms

CCS: California Current System

CDFW: California Department of Fish and Wildlife

CFMP: Conservation and Fishery Management Plan

CPUE: Catch-Per-Unit-Effort

CSWG: Competitive State Wildlife Grant

DO: Dissolved Oxygen

ESA: Endangered Species Act

FDA: U.S. Food and Drug Administration

FMP: Fishery Management Plan

HAB: Harmful Algal Bloom

HCR: Harvest Control Rule

LRP: Limit reference point

MFMP: Marine Fisheries Management Plan

MRP: Marine Resources Program

MSC: Marine Stewardship Council

MVP: Minimum Viable Population

NOAA: National Oceanic and Atmospheric Administration

OAR: Oregon Administrative Rule

ODA: Oregon Department of Agriculture

ODFW: Oregon Department of Fish and Wildlife

OFWC: Oregon Fish and Wildlife Commission

ORS: Oregon Revised Statute

OSP: Oregon State Police

OSU: Oregon State University

PDO: Pacific Decadal Oscillation

PLD: Pelagic Larval Duration

PSMFC: Pacific States Marine Fisheries Commission

SCUBA: Self-Contained Underwater Breathing Apparatus

SPR: Spawning Potential Ratio

SST: Sea Surface Temperature

TAC: Total Allowable Catch

vii. Definitions

Catch-per-unit-effort (CPUE): An indirect measure of relative abundance of a target species, derived from the quantity of catch divided by a defined measure of fishing effort undertaken to obtain the catch.

Intertidal: The area in Oregon coastal bays, estuaries, and beaches between mean extreme low water and mean extreme high-water boundaries (OAR 635-005-0240).

Landing: The portion of the catch that is landed in ports.

Nearshore: The area from the outer boundary of Oregon's Territorial Sea at three nautical miles to the supratidal zone affected by wave spray at extreme high tides, and up into the portions of estuaries where species depend on the saltwater that comes in from the ocean (ODFW, 2016).

Recreational fishery: The legal harvest of living marine species for personal use (as defined in ORS § 506.006).

Spring transition: The transition from a winter downwelling state to a summer upwelling state along the west coast of North America because of winds from the south shifting to a predominately equatorward direction.

Stock: An aggregation for management purposes of fish [or shellfish] populations which typically share common characteristics such as life histories, migration patterns, or habitats (OAR 635-007-0501).

Shell Length (SL): Measurement of abalone size, using calipers to measure the length of the shell from posterior to anterior side.

Take:

- *As defined under the U.S. ESA* – To harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct (16 U.S.C. § 1532(19)).
- *As defined under Oregon law* – Fish for, hunt, pursue, catch, capture or kill or attempt to fish for, hunt, pursue, catch, capture or kill (ORS § 506.006).

Upwelling: The offshore movement of surface shelf waters and subsequent replacement by cold, nutrient-rich deep waters from off the shelf.

B. Resource Analysis

This analysis provides a description of the red abalone (*Haliotis rufescens)* resource in Oregon, along with a review of its biology and ecology, synthesis of available data, and analysis of the stock status. Presented are both non-fishery and fishery-related threats to red abalone and its habitats along with recommendations for sustainable harvest strategies. Finally, a prioritized list of information gaps and research needs related to red abalone and the Oregon fishery is provided.

This plan is a comprehensive management and conservation tool for the red abalone population in the state waters of Oregon.

Red abalone were first described as a species in 1822 (Swainson, 1822). The red abalone (phylum Mollusca; class Gastropoda; subclass Prosobranchia; order Archaeogastropoda; family Haliotidae) is the largest species of abalone in the world (Cox, 1962; Geiger, 1999). Red abalone are dioecious (separate sexes) broadcast spawning marine invertebrates that live in the rocky nearshore, feeding on drift kelp and living sedentary lives. Available data for the red abalone fishery in Oregon includes fishery dependent data from both the recreational and commercial efforts, and fishery independent survey data. Threats to the resource and fishery include increased fishing pressure, habitat impacts, changing ocean conditions, disease, ecological shifts, and predation. Harvest levels in Oregon have historically been low in comparison with California, with the highest annual average take by the recreational fishery in Oregon reaching 299 individual red abalone (2017). It is expected that harvest levels of red abalone will also be low in the future reflecting the normally low population levels in Oregon. More information about the biology and ecology of red abalone including recruitment variability, movement studies, natural mortality, and potential marine mammal interactions, as well as potential impacts of climate change is needed to accurately assess the population and guide management.

Red abalone are an important part of the rocky intertidal and subtidal community and are the target of recreational fisheries.

i. Biology and Ecology of Red Abalone

Effective fisheries management is dependent upon a comprehensive understanding of the life history characteristics of the targeted species. Several studies focusing on red abalone have been; however, their biological and ecological requirements are highly complex and not completely understood. This subsection synthesizes current and historical literature on the biology and ecology of red abalone.

a. Biology

a. Range and dispersion

Red abalone occur throughout the rocky intertidal and subtidal waters from Coos Bay, Oregon to Baja California, Mexico (Cox, 1962; Geiger, 1999). The biogeographic species range is influenced by the California Current System (CCS). Each current system is associated with unique environmental characteristics that influence the habitat available to red abalone and consequently the biology and ecology of the species at the local level.

The CCS extends from the transition zone along the North American west coast at latitudes of 50° North southward to 15-25° North (Checkley and Barth, 2009). The CCS is comprised of the equatorward flowing California Current (CC), coastal jet, the California Undercurrent (CU) and seasonal currents such as the northward Davidson Current. The system is characterized by several complex physical processes including seasonal wind-driven upwelling, variable local wind dynamics, and freshwater input (Hickey and Banas, 2008). Interannual variability in these processes are closely tied to environmental conditions which impact red abalone throughout their life cycle.

Red abalone are patchily dispersed throughout the rocky intertidal and subtidal environment, commonly found in areas protected from high impact hydrodynamic systems on rocky, rugose locations where they have consistent access to drift kelp (Ault et al., 1985a; Mclean, 1962). While the larval period of red abalone is highly affected by currents, as adults they live sedentarily, moving throughout their habitat only when food availability is low or presence of predators (Ault and Demartini, 1987).

Red abalone are thought to be one connected population throughout the west coast of North America. Genetic studies have confirmed that red abalone populations in southern and northern California are genetically connected through larval dispersal (Gruenthal et al., 2007). Genetic linkage of Oregon red abalone to larger population was explored as a part of this management plan and are described in the genetics section below.

b. Morphology

General morphological characteristics of red abalone (Figure 11). Adult red abalone vary in color, but typically have a large, brick red shell with 3-4 open respiratory pores and a large soft body that is surrounded by a shell-secreting mantle, a head with specialized structures for sensing and eating food, and a large muscular foot (Cox, 1962). They have a large, flattened spire on their posterior dorsal side. Their ventral side has a muscular foot used to attach to substrates and locomote. Covering the foot and protecting the abalone’s internal anatomy is an epipodium, a large fleshy extension of the mantle. The epipodium in red abalone is pigmented black and has many sensory tentacles surrounding their body (Ault et al., 1985; Cox, 1962).

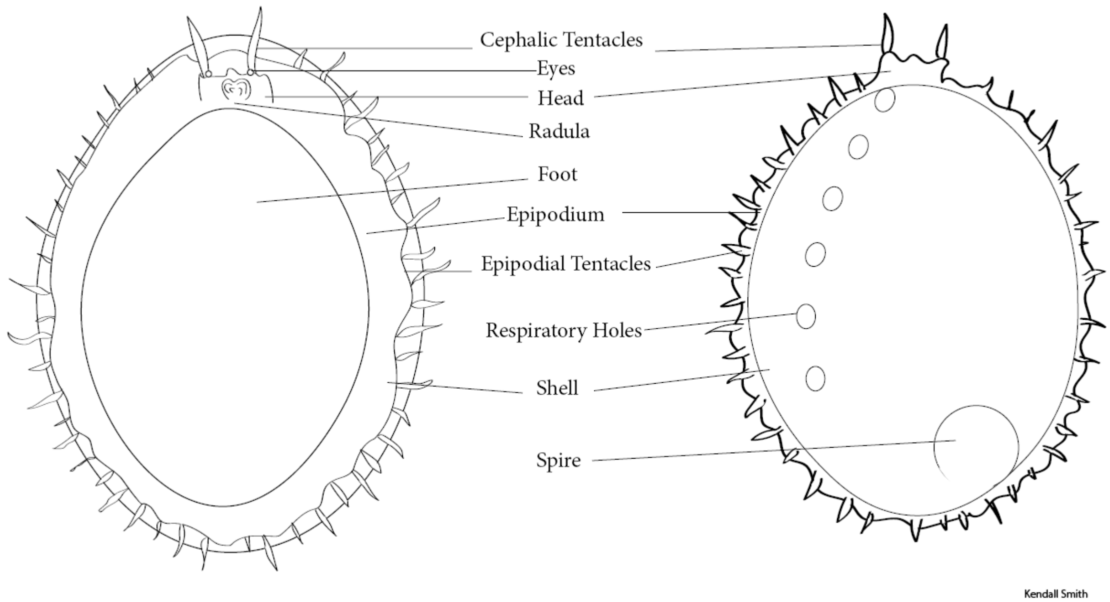

Figure 11: General external morphology of red abalone (*Haliotis rufescens*).

c. Life History

Like other abalone, red abalone exhibit a bi-phasic life history strategy that includes long-lived adults and short-lived larvae. Key stages in the abalone life cycle are shown in Figure 12.

i. Spawning

Red abalone spawn seasonally, spawning times vary across their range. In the northern part of their range, peak spawning is cued by temperature changes, whereas in the southern portion of their range, red abalone may spawn twice a year (Price, 1974). However, laboratory studies on red abalone from southern California spawned every month of the year (Leighton, 1974). Northern California red abalone have been found to spawn from April through July. Both laboratory and field studies found that red abalone in Central California (Monterey) are capable of spawning and showing signs of recruitment year-round (Boolootian and Giese, 1962; Hart et al., 2020; Leighton, 1974; Price, 1974). Lab studies of specimens from Northern California have been found to spawn during the spring transition and downwelling conditions, when onshore transport of ocean surface waters and higher sea surface temperatures occur; however, earlier studies suggested that temperature did not correlate with spawning and that all three types of spawning might occur within a local population of red abalone (Young and DeMartini, 1970). In Oregon, spawning studies have been rare and largely unsuccessful, with laboratory-induced spawning failing to result in any fertilized embryos or larvae (Lukas, 1973; Nielsen, 1967). Field observations of red abalone spawning in Oregon are rare; however, biologists have not noted spawned out gonads even among samples examined from expected spawning seasons July (Pers. Comm. Scott Groth). Spawning stimuli for red abalone are not well understood, laboratory studies have shown that the addition of hydrogen peroxide (H_2O_2) to seawater causes male and female red abalone to spawn due to activation of enzyme catalysis in their reproductive cells; however, it is not known what causes induction of spawning in the wild (Morse et al., 1977) It has been suggested that the importance of adding hydrogen peroxide to seawater for natural spawning could be indicative of both temperature and additional environmental oxygen possibly indicated by food availability or downwelling conditions (Degnan and Morse, 1995)

ii. Reproduction

Abalone are dioecious broadcast spawners where adults with separate sexes that release gametes into the water column simultaneously. If fertilization is successful, a lecithotrophic (non-feeding) trochophore larva develops(Carlisle, 1962; Crofts, 1937). After (5-14 days) (Searcy-Bernal, 1999) floating through the water column as a trochophore larva, they metamorphose into a veliger larva and develop sensory structures, denoting the onset of competency to complete settlement and metamorphosis. Once cephalic tentacles develop abalone veliger larvae are competent and able to settle. Larval settlement occurs when acceptable habitat and conditions are detected, characterized by ideal water temperature, presence of crustose coralline algae, and adult conspecifics.

Broadcast spawning is a reproduction strategy known to be rarely successful; however, red abalone have adapted to increase reproductive success. Three common adaptations to improve broadcast spawning success are: 1) gamete release synchrony, 2) spawner aggregation, and 3) sperm volume. Red abalone have incorporated each of these adaptations. They are found to aggregate when environmental conditions are ideal (Button, 2008) and spawning studies have found that spawning is triggered when a nearby conspecific first releases gametes (Morse et al., 1977). Lastly, red abalone males produce large amounts of sperm volume to body ratio (Rogers-Bennett and Kashiwada, 2004).

Following settlement and metamorphosis of red abalone veligers into newly settled juveniles, cryptic behavior is common until spawning age is reached (3 or 4 years for females) (Ault et al., 1985). Specifically, red abalone become sexually differentiated at a shell length (SL) of 50mm, but reach sexual maturity, denoted by thick ovary tissue and mature oocytes, at variable sizes for females. (Rogers-Bennett and Kashiwada, 2004) found that at a size of 130mm SL, all female red abalone had reached sexual maturity, and males reach sexual maturity at smaller sizes (60mm). Fecundity in red abalone increases with size, reaching a peak at a SL of 215mm, and found to become senescent, indicated by a high percentage of necrotic (dead) eggs. This indicates that larger individuals contribute to recruitment at an unequally high rate; however, the largest red abalone may be senescent.

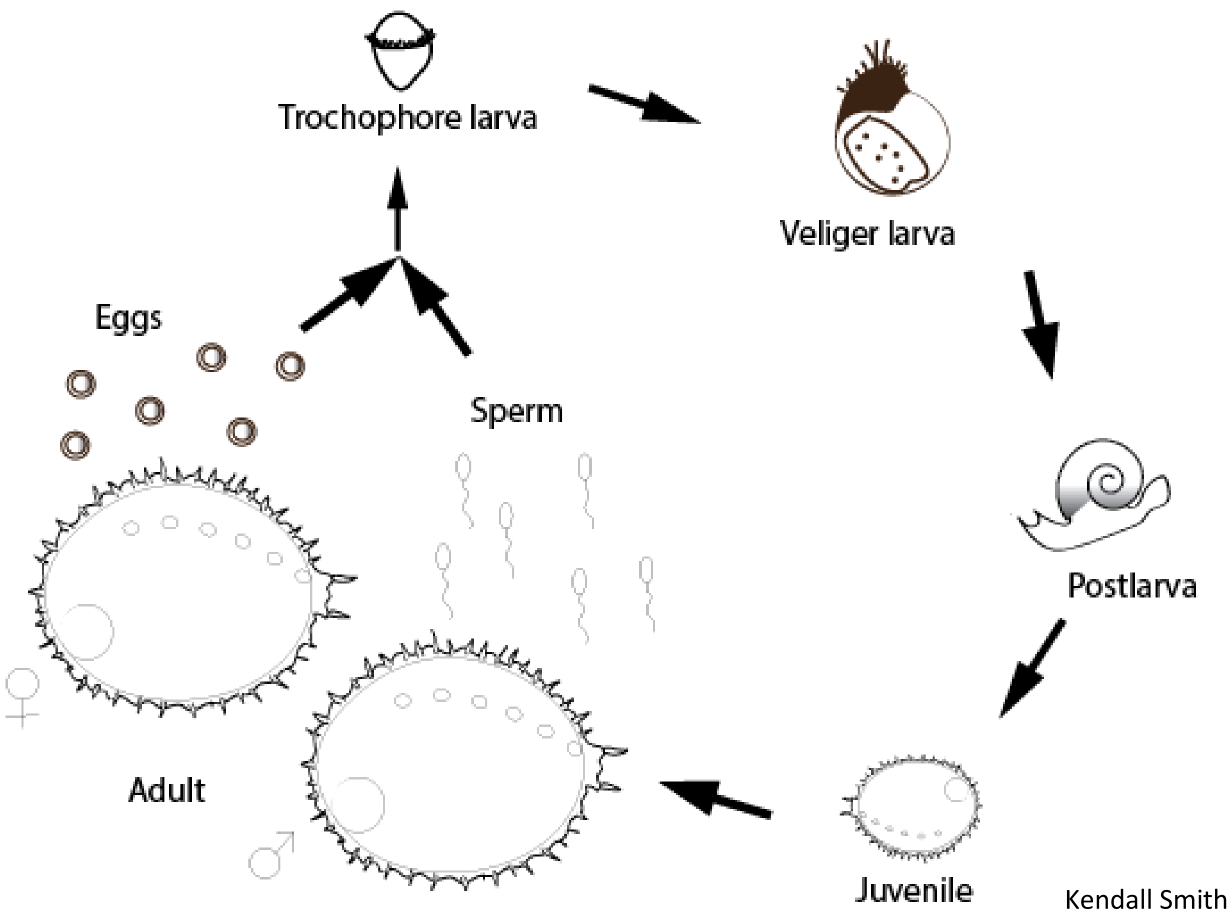

Figure 12: Life cycle of red abalone (*Haliotis rufescens*).

iii. Growth

Red abalone exhibit variation of growth which can be attributed to differences in: 1) temperature, 2) food availability, and 3) population density (Jiao et al., 2010). However, growth rates are similar among all species of abalone in their first few years (Ault, 1985). Following initial settlement, post-larval red abalone remain on coralline algae for two weeks and then find more cryptic habitats. After 1 to 3 months, red abalone have a shell length (SL) of about 2mm and begin to form respiratory pores. At the end of their first year, red abalone are about 20mm SL and by the end of the third to fourth year they are 75-100mm SL (Ault, 1985). Although red abalone grow to large sizes, they grow slowly (Leaf et al., 2008). Red abalone in northern California require approximately 12 years to reach 178mm SL in California. Further, this study determined that comparatively, red abalone in northern California had a slower growth rate than those in southern California (Rogers-Bennett et al., 2007). Variability in length at age within and among cohorts can be a result of ocean conditions (Jiao et al., 2010). Variability in size at age may also be a result of population levels, size distribution, genetic composition, and individual energy allocation(Jiao et al., 2010). Lastly, size selective mortality by predation can lead to a truncated size distribution (Hamilton 2007).

iv. Maximum Size

Red abalone are the largest species of abalone in the world (Cox, 1962). The largest individuals have been found in Oregon waters, with the maximum recorded SL of 318 mm (12.5 inch) (Groth and Smith, 2022) and surveys indicating a truncated size distribution (Figure 13). As size and growth rate are often more indicative of the surrounding environment and specific biological conditions, it is important to understand and quantify size-at-age for management and biological purposes.

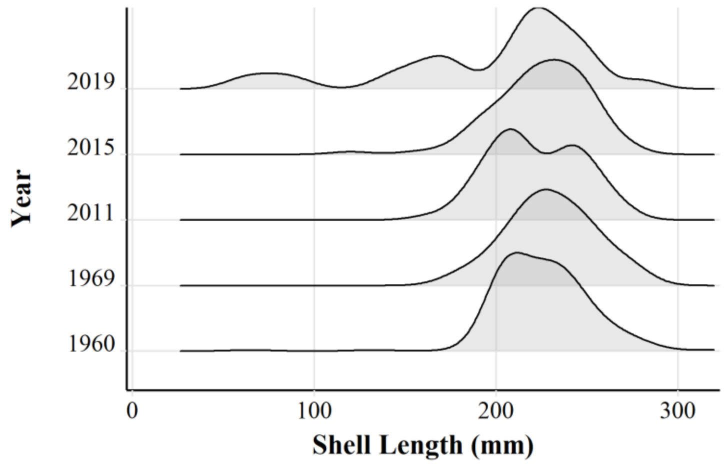

Figure 13: Histogram of red abalone (*Haliotis rufescens*) shell length (SL) mm from survey data (1960, 1969, 2011, 2015 and 2019) in Brookings, OR; from (Groth and Smith, 2022).

v. Age

Size-at-age is an important metric for understanding appropriate Minimum Legal Size (MLS), in fishery management. Mean age at size for abalone is variable and difficult to estimate, studies focused on quantifying age-at-size for red abalone in California have utilized diverse methods, but their results differ in their conclusions. Mark-recapture studies have determined that red abalone in northern California have differing natural mortalities based on size-class, habitat, and predator presence. Specifically, the smallest size class (<100mm SL) had the highest mortality and mean annual mortality rates decrease with increasing size (Leaf et al., 2007). Another study of northern California red abalone found that it takes about 12 years to reach 178mm. (Leaf et al., 2008) utilized bomb generated radiocarbon to age a large (251mm SL) red abalone which was estimated to be 30-33 years. Maximum age of red abalone has not been determined but is estimated to be upwards of 50 years (Cox, 1962; Karpov et al., 1998; Leaf et al., 2008). Age studies have not been performed for red abalone in Oregon, but as environmental conditions are like those in northern California, the size-at-age growth parameters may be appropriately applied to Oregon.

d. Genetics

The genetic composition of a population is an increasingly important body of information for understanding the health and size of an exploited species. Broadcast spawning marine invertebrates are difficult to monitor due to the fluid and somewhat variable nature of larval dispersal (Mccormick et al., 2012; Mikaye et al., 2017; Miller et al., 2014; Rogers-Bennett et al., 2016; Wang, 2005). Maintaining genetic diversity within an imperiled, sensitive, or at-risk species is of high priority when considering conservation, and it is vital to understand how populations are sharing genetic information, how often, and how these characteristics influence the health of that population(An et al., 2012; Díaz-Viloria et al., 2009; Gruenthal et al., 2007; Hamm and Burton, 2000). Genetic studies have not been performed for red abalone in Oregon previously. In 2021, red abalone from four discrete locations in Oregon were sampled and sent for genetic analysis, in addition to samples collected from a previous effort in Oregon in 2008-2009. Following DNA extraction and sequencing of samples from both sampling events in Oregon, results were compared with red abalone genetic samples from northern and central California collected as part of a larger genomics project organized by the Whitehead lab at UC Davis. Extractions were performed by Dr. Joanna Griffiths, and preliminary analysis was performed by Kendall Smith. Results of this effort provide preliminary evidence that all four subpopulations within Oregon are genetically connected to populations in central and northern California (Figure 14). Principal Component Analysis (PCA) revealed that the red abalone samples were closely related with a single cluster centered in four quadrats along the PC1 axis (Principal Component 1), indicating a high level of genetic similarity among populations.

Biological implications for these findings can be explained by considering their larval dispersal methods and the variability of environmental conditions associated with successful reproductive events. Management implications for these findings are discussed in the Management and Conservation Strategy section of this plan, with particular emphasis in the recommended actions section.

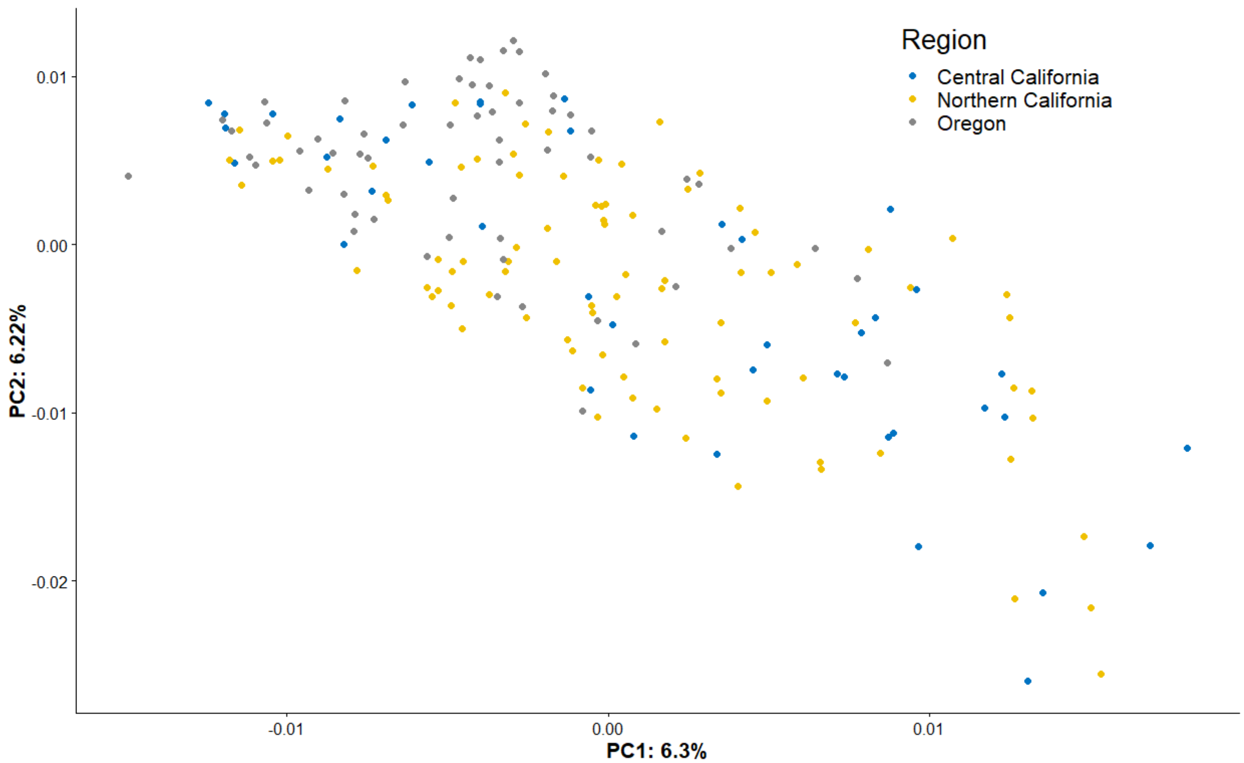

Figure 14: Principal Components Analysis (PCA) plot for red abalone (*Haliotis rufescens*) samples collected from 1990-2021 from central and northern California, and Oregon (preliminary analysis through collaboration with UC Davis and Whitehead lab) by decade of collection.

b. Ecology

a. Habitat and Movement

Red abalone habitat is characterized by shallow, rugose, rocky areas with consistent access to drift kelp. Red abalone persist at variable depths and habitat types throughout their range, living deeper in southern California (down to 100 feet/30m), shallower in northern California (down to 20 feet/6m) (California Department of Fish and Game, 2005) and shallowest in Oregon, with catch permits reporting average depths of 10 ft/3m (Groth and Smith, 2022). Red abalone can live at shallower depths in northern California and in Oregon due to the cooler water temperatures of 8-15° C, compared to warmer waters in central (10-15° C) and southern California (15-21° C) (California Department of Fish and Game, 2005).

Adult red abalone live mostly sedentary lives; however, some studies have found that red abalone may move considerable distances in response to food availability. In northern California, red abalone may occupy shallower habitats in the spring and winter and move to deeper waters in the summer and fall (Ault and Demartini, 1987). Red abalone also exhibit habitat movement when transitioning through life stages, with juveniles occupying more cryptic habitats and moving into more exposed habitats as they grow, and dietary requirements shift (Ault et al., 1985; Ault and Demartini, 1987; Tegner and Butler, 1989).

b. Abiotic Factors

The physiological tolerance of an organism to changes in environmental conditions (e.g., temperature and salinity) is closely tied to their dispersion and habitat. Ocean temperatures strongly influence spawning in red abalone and changing ocean temperatures could affect their biogeographic range through impacts on reproduction and overall health (Kawana et al., 2019; Rogers-Bennett et al., 2010). Ocean temperatures impact reproduction potential in red abalone, affecting sperm production in males, mature oocyte production in females and fertilization success. Specifically, lab experiments with red abalone found that at 18℃, 71% of males had no sperm following 6 months of exposure(Rogers-Bennett et al., 2010). Females were less affected overall by temperature increases, but fertilization of ova was found to occur at temperatures of 12-15˚C, whereas an increase to 18˚C decreased fertilization from 100% to 80%. As discussed in the reproduction section, spawning stimuli of red abalone is not well understood.

c. Diet

Red abalone are herbivores that feed on algae and kelp, with a preference for drift kelp. In Oregon, bull kelp, *Nereocystis luetkeana*, is the dominant canopy-forming kelp, present in high densities seasonally and a primary food of red abalone. Red abalone eat other types of algae, and their shell can differ in color based on whether abalone are eating brown, green or red algae (Ault et al., 1985). In ideal environments, red abalone can acquire all of their dietary needs from drift algae. When algal densities are low, red abalone will leave their crevices and rock overhangs to forage for food at the base of kelp stalks (Ault and Demartini, 1987; Rogers-Bennett and Catton, 2019)

d. Predation

Red abalone have two distinct stages in their life cycle with differing implications for trophic web interactions. Red abalone juveniles (<100mm SL) are preyed upon by many benthic marine organisms, and therefore exhibit cryptic behavior by remaining under rocks, cobble, and seeking shelter under red sea urchin spine canopies (Tegner and Butler, 1989). As red abalone reach sexual maturity and grow, they face predation from larger predators that vary depending on the geographic species distribution of the red abalone population. As post larval and small juveniles <100mm, red abalone are predated upon by sea stars, crabs, octopus, and fishes. Juvenile red abalone have been found to have high mortality due to predation, which is thought to be a main driver in cryptic behavior observed in juvenile red abalone(Ault et al., 1985; Ault and Demartini, 1987; Rogers-Bennett et al., 2016; Rogers-Bennett and Pearse, 2001).

Adult red abalone have few predators, especially as they increase in size. Sea otters (*Enhydra lutris*) are a main predator of red abalone, to the extent that they drive population-level behavioral effects. Specifically, in areas where sea otters are present, red abalone are smaller in size and are located exclusively in crevices and under rock overhangs. In contrast, areas where sea otters are absent, red abalone grow to larger maximum and average sizes and occupy areas outside of crevices (Hines and Pearse, 1982; Watson, 2000; Wendell, 1994).

ii. Available Data

The ODFW Marine Resources Program (MRP) has collected data periodically on red abalone since the 1950s. The various data sources that have contributed to the understanding to the Oregon red abalone fishery and population are: 1) fishery dependent data 2) fishery independent data and 3) other data (i.e., educational/scientific take and enhancement projects). This section catalogs known data sources for Oregon's red abalone.

ODFW Data Confidentiality

Data collected, prepared, or held by ODFW are subject to public disclosure under Oregon public records law (ORS § 192.314). However, certain fishery and other resource-related data collected by the ODFW Marine Resources Program are considered confidential data; accordingly, these data are conditionally exempt from the legal requirement to allow inspection of public records (ORS § 192.345).

In general, biological and research data about fishery species and habitats are not confidential. However, information related to fishing business operations (e.g., how and where fish are caught, income from fishing) is confidential. This includes commercial fish landing receipts, commercial fishing logbooks (e.g., OAR 635-005-0445), and operational data from recreational charter fishing vessels.

ODFW regularly receives requests for confidential data for use in various analyses (e.g., biological, regulatory, economic). ODFW evaluates all requests on an individual basis and will opt to provide non-confidential data whenever possible. To accomplish this, confidential data may be redacted, aggregated, or summarized to prevent any individually identifiable information from being released. If it is determined to be in the public interest, ODFW may release confidential data, protected through a non-disclosure agreement to restrict the use and distribution of confidential fishery data. In general, confidential data are only released to researchers conducting science that will improve the state's ability to manage Oregon's fishery resources.

a. Fishery Dependent Data

a. Recreational Fishery

In Oregon, harvest of red abalone has been primarily by the recreational sector. Available data from the recreational red abalone fishery (1950s-2018) was collected through returned catch report permits. Catch report permits were first introduced in 1973 at no cost to obtain more information about the fishery and catch rates. Available data from permits contain catch and permittee information, including: 1) number caught 2) catch location 3) catch depth 4) fishing method and 5) permittee's county of residence. Two eras of catch report permit data are available, 1973-1979 and 1996-2017. In 1973-1979, an annual average of 126 catch reporting permits were issued, with an annual catch average of 28 red abalone. In 1996-2017, both number of participants and annual catch increased, with an annual average of 175 permits issued (Figure 15) and an annual catch average of 145 red abalone (Figure 16). Catch area data was not required prior to 2005, but data from all permits with catch area demonstrated a strong focus on the south coast, particularly near the Brookings area. Specifically, 95% of catch occurred near Brookings, whereas 3% occurred near Port Orford, and the remaining catch (<1%) near Gold Beach and Coos Bay (Figure 17). Among the three methods of catch SCUBA (self-contained underwater breathing apparatus), free dive, and shore pick, 51% used SCUBA with a mean depth of 5.2 m, 29% used free dive with a mean depth of 4m and the remaining 19% used shore pick with a mean depth of 0.3m (n=2,169) (Groth and Smith, 2022).

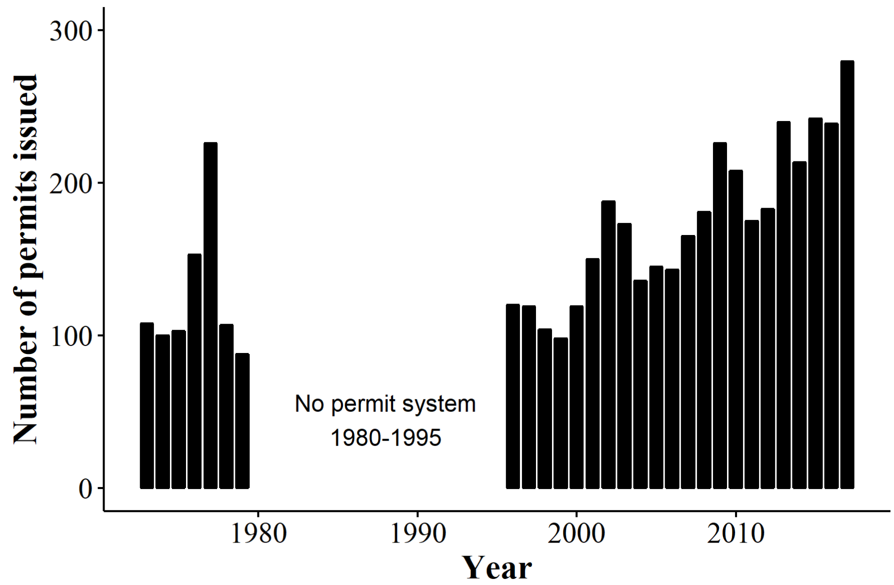

Figure 15: Recreational red abalone (*Haliotis rufescens*) permits issued from 1973-1979 and 1996-2017 in Oregon, from (Groth and Smith, 2022).

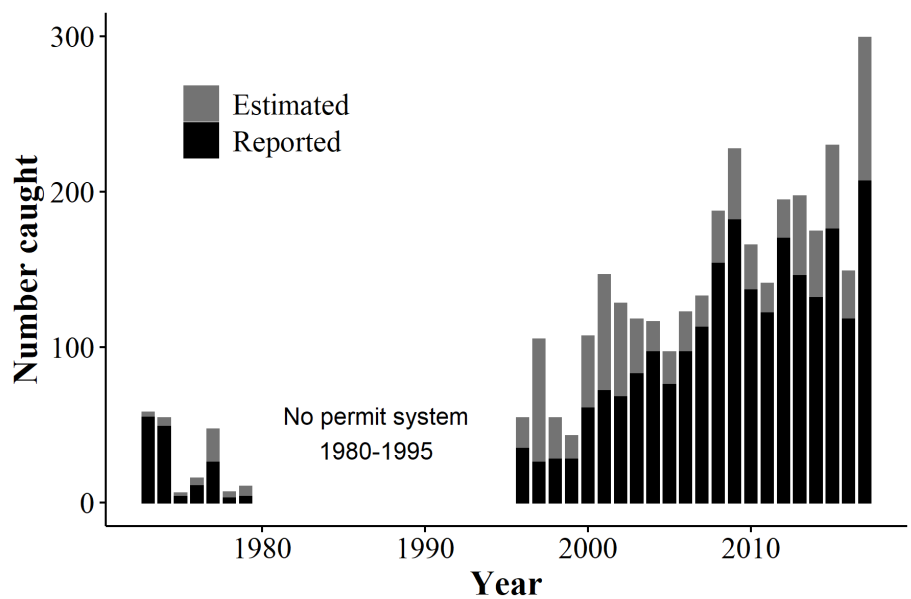

Figure 16: Recreational red abalone (*Haliotis rufescens*) fishery catch from 1973-2017 in Oregon, from (Groth and Smith, 2022).

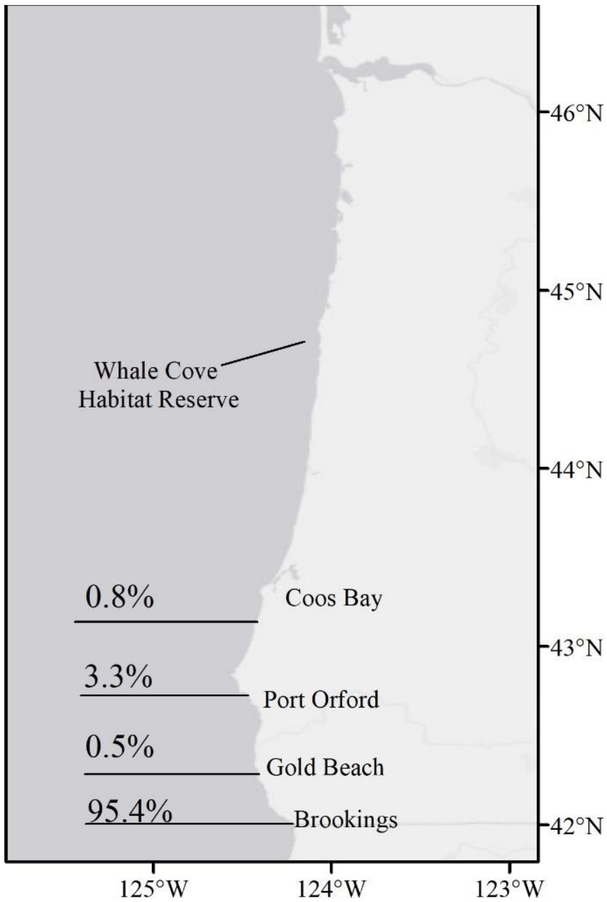

Figure 17: Percentage of recreational red abalone (*Haliotis rufescens*) fishery catch by area from 1996-2017 in Oregon (n=1894) from (Groth and Smith, 2022).

b. Exploratory Commercial Fishery

A small exploratory fishery operated in southern Oregon from 1958-1962. Available data from this effort include dive reports and red abalone size measurements, providing qualitative data about red abalone habitat in Oregon and abundance. 58 dives were completed from 1958-1960, with at least 111 red abalone caught and measured. The exploratory effort was terminated in 1962 as momentum lowered and only a few dives were performed (Snow, 1962).

b. Fishery Independent Data

Survey data for red abalone in Oregon is limited, as quantitative surveys were only first attempted in 2011 and not formalized until 2015. Prior to 2011, two iterations of qualitative surveys were performed by ODFW. First by contract from 1958-1962, in which red abalone were removed, measured and their location was noted. The second iteration of qualitative surveys was performed by ODFW divers from the 1960s-1990s as spot checks to bolster further understanding of the stock.

The first attempt at quantitative surveys occurred over a two-day period in June 2011, evaluating polygonal index site surveys and timed surveys. Results of this survey effort determined that random transect locations for index sites would not accurately detect abalones in Oregon, and timed surveys can be used for size distribution data collection, but not density measurement (Table 5).

In 2015, the first quantitative surveys were performed in Oregon, with two index sites chosen where the fishery operates in Port Orford and Brookings. Forty-four 30 x 2m subtidal belt transects were performed, 20 in Port Orford and 24 in Brookings respectively (Table 6) Surveys are planned to be repeated in 2022 at both sites (Port Orford and Brookings), funded by the Competitive State Wildlife Grant (CSWG).

Table 5: Number of red abalone (*Haliotis rufescens*) seen in timed dives by year (1969, 2011) in Brookings, Oregon from (Groth and Smith, 2022).

Year	Number seen	Survey minutes	Abalone/hour
1969	46	250	11.15
2011	55	127	24.39

Table 6: Red abalone (*Haliotis rufescens*) densities (per m^2) from fishery independent index sites in 2015 and 2019 by port in Oregon from (Groth and Smith, 2022)

Year	Port	
	Brookings	Port Orford
2015	0.038	0.030
2019		0.015

c. Other Data

a. ODFW's Educational and Scientific Take Permitting System

In addition to fishery take, ODFW has an educational and scientific take permitting system that has allowed take of abalone species. This scientific take of abalone is regulated through ODFW's educational and scientific take permitting system (ORS § 508.111). However, this take is issued based on scientific merit of proposed project with consideration of population levels, and it is currently prohibited to take abalone of any kind unless specifically noted by this permit. A summary of reported educational and scientific take of abalone in Oregon is available in a table below (Table 7). There has been no previous reported take of red abalone prior to 2021.

Table 7: Requested and reported educational and scientific take in Oregon 2002-2022. NR denotes take that has not been reported.

Year	Requested take	Actual take	Mortality	Action
2021	122	1	0	Collect
2022	151	NR	NR	Harass

b. Enhancement Projects

As abalone fisheries are difficult to manage sustainably and have a large amount of interested harvesters, projects to enhance the population of abalone are common. In Oregon, two enhancement efforts targeted at bolstering the fishery and increasing the stock were employed with varying results. The first project took place in the 1960s at Whale Cove (a no-take reserve), which is just north of Depoe Bay, OR and is 100 miles north of the biological range extent in Coos Bay, OR. The goals of this effort were to create a new fishing opportunity for red abalone in Oregon and to create a spawning stock that was protected from fishing pressure (Nielsen, 1967). Between 1967 and 1974, a total of 5660 juvenile and 277 adult red abalone were placed in Whale Cove from both hatchery stock and northern California wild populations. The results of this effort did not increase fishing opportunities in Oregon. However, this project did provide researchers with some information about red abalone growth, age, and reproduction in Oregon (Groth and Smith, 2022).

The second enhancement project in Oregon was designed to enhance the spawning stock of wild red abalone in Oregon and took place between 1994-2002 as a partnership with Oregon State University (OSU)(Golden and Langdon, 1995). Juvenile red abalone were reared from adult red abalone collected in Oregon; however, the results of this project are unknown because monitoring was not in place at the time. Several red abalone from this project were introduced in Oregon waters near Coos Bay in 2002 (Groth and Smith, 2022).

iii. Analysis of Stock Status

Stock status of red abalone has been tracked by relative indices in California (Karpov et al., 2000, 2001, 1998). In Oregon, methods have been variable and infrequent, just beginning a similar program of belt transects within harvest areas in 2015. Further, the population is difficult to survey due to both habitats and red abalones' cryptic and elusive nature. While traditional methods give a good relative index, they are costly and difficult to perform in Oregon. Adaptive and non-traditional methodologies could be assessed to improve effectiveness for quantifying red abalone in Oregon. Utilizing the stock assessment metrics and application of California's red abalone population is a useful convention that may be considered for Oregon. Sections below detail considerations for Oregon's red abalone stock status.

a. Stock Assessments

Stock assessments for red abalone in Oregon are limited, with one index survey performed in 2015 at two sites. Findings of this survey indicated much lower densities of red abalone than results from fished areas in California.

Stock assessments for red abalone in northern California historically occur at eight index sites, with four sites in Sonoma County and four sites in Mendocino County. Index sites were chosen based on catch data, with chosen sites making up 48% of fishery catch overall (California Department of Fish and Game, 2005). These sites are meant to allow for early detection exceeding California LRPs. For each site, 36 randomly selected depth stratified 30 x 2m transects are performed, taking approximately three years to complete. To compare these 3-year surveys, relative time periods were utilized to determine changes in the red abalone population. An evaluation of these surveys in 2013 indicated non-actionable changes to red abalone densities between baseline surveys in 1999-2000 and 2003-2007 but trended downward 36% between 2003-2007 and 2009-2012. Recent stock assessments (2016-2018) in northern California indicated very sharp decline in red abalone populations, with densities lowering between 2016-2017 by 48-82% and further declines of 43-96% between 2017-2018 (Rogers-Bennett and Catton, 2019).

In 2019, ODFW personnel revisited one site (Port Orford) and performed belt transect surveys that demonstrated a similar decline in densities, with a decrease from 0.15 red abalone per m^2 in 2015 dropping to 0.03 red abalone per m^2 in 2019 (Groth and Smith, 2022)

b. Limit Reference Point

Limit Reference Points (LRPs) are data driven metrics which are designed to make decisions to effectively protect and manage natural resources (Caddy and Mahon, 1995). In the red abalone fishery in Oregon, none are currently set. In CA, LRPs for the recreational red abalone fishery in northern California are in place and have been modified over time.

In 2005, CDFW published and adopted the Abalone Recovery and Management Plan (ARMP), which details aspects of biology, stock status, ecology and management for abalone fisheries and recovery in California (California Department of Fish and Game, 2005). Based on a long history of population trend data Minimum Viable Population (MVP) was determined to be 0.66 red abalone per m^2 to sustain fishing, and 0.2 red abalone/m^2 for unfished recovered populations. If densities fall below 0.2 red abalone per m^2, the population could be susceptible to collapse, this metric was determined using minimum spawning densities evaluating historic levels at a designated spatial extent (Shepherd and Brown, 1993), and densities that preceded the decline of red abalone in southern California (Karpov et al., 1998; Tegner et al., 1989). Using the MVP for red abalone in northern California, the catch reduction trigger was set at 0.5 red abalone per m^2 which would require considerations for reducing catch. The level set for closing a particular fishing site was set at 0.25 red abalone/m^2. In addition to these LRPs, a total allowable catch (TAC) was determined for all northern California sites combined.

In Oregon, measured densities from fishery independent surveys have been below the threshold set by California, with 2015 surveys indicating a density of 0.15 red abalone/m^2 and partial surveys in 2019 with an even lower density of 0.03 red abalone/m^2. LRPs for red abalone utilize density and biological metrics (SPR, survey densities, etc.). If this approach were to be applied in

Oregon, management would have to rely on sparse data of populations at the edge of their range, therefore other potentially empirical metrics should be integrated.

c. Synthesis of Results

Application of density levels from surveys to management actions is variable for abalone fisheries worldwide and differs based on the size of the fishery, localized environmental and biological factors. In Oregon, densities for red abalone have not been used to set a TAC or adaptive management by fishery zone.

In California, the application of survey and catch data to management for abalone fisheries has been updated through time. In 2005, CDFW adopted the ARMP which regulated catch levels in northern California's red abalone fishery. A TAC is set (400,000 red abalone) based on projected catch then reduced (280,000 red abalone) and adjusted based on actual catch on an annual basis through reductions or increased in daily and annual limits. Further changes to this strategy are currently in progress, with a Management Strategy Evaluation (MSE) completed in 2018 by The Nature Conservancy (TNC), evaluating previous management strategies outlined in the ARMP. The results have been incorporated into a new FMP (Summary of the Management Strategy Integration Process for the North Coast Recreational Red Abalone Fishery Management Plan) prepared in 2020 (Jackson et al., 2020). The review focused on the need for creating flexible and site-specific management objectives with spatial considerations in mind.

<u>iv. Threats to the Red Abalone Resource</u>

a. Fishery Related

As fisheries target specific organisms and increase in efficiency with time, increased fishing pressure can threaten a resource through removal of more individuals than the population can effectively replace. The recreational red abalone fishery in Oregon increased in popularity reaching its peak just before the fishery was suspended in 2018 (Figure 15). The demand for abalone fishing opportunities has increased worldwide as environmental conditions have shifted, causing further strain on the imperiled population. In addition to increased fishing pressure, red abalone are often harvested from "hotspots" where many abalone are aggregated. Removing red abalone from these aggregations can have adverse effects on both reproduction and overall population health. Further, red abalone are often targeted by their large size as trophy abalone (SL>254mm), especially in Oregon where the recreational fishery is primarily a trophy fishery. Since red abalone produce more eggs as they increase in size, removing the larger individuals has the consequence of unequally affecting reproduction (Rogers-Bennett and Kashiwada, 2004). Declines in kelp density correlated with warming events have led to more emergent behaviors in red abalone, allowing them to have less food and more exposure to predation (Rogers-Bennett et al., 2021, 2019). Increased exposure of red abalone can cause a misinterpretation of densities in Oregon, primarily by recreational users that are used to difficulty in locating red abalone for harvesting.

b. Habitat Impacts

Red abalone habitats in Oregon are limited and recently experienced changes. Red abalone are only common in the southernmost part of the state, primarily in the ten most southern miles (16 km) of Oregon's 352-mile (566 km) coastline. Red abalone habitat is characterized by rocky reefs and kelp beds (Ault et al., 1985b). In recent years kelp has dramatically reduced across the west coast, deeply affecting abalone populations (Kawana et al., 2019; Rogers-Bennett and Catton, 2019) Warm water conditions and kelp density loss have led to increased red abalone mortality due to starvation. In addition to ecological changes, freshwater inputs associated with development have been reported to cause mass die offs in Oregon (Groth and Smith, 2022). Further, sediment deposits are likely due to a combination of coastal construction and development, and it will be important to monitor the effects on the nearshore communities.

c. Changing Ocean Conditions

Environmental conditions are changing, and effects have been detected and are expected to increase. Ocean condition shifts that will impact red abalone populations include ocean acidification, warming sea surface temperatures, decreased oceanic oxygen and other ecological stressors.

a. Ocean Acidification

Ocean acidification has increased and is expected to accelerate (le Quéré et al., 2016). Higher acidified seawater has consequences for different life stages and processes of marine organisms. Benthic organisms that live deeper and have shells made from calcium carbonate ($CaCO_3$) may be the most vulnerable to ocean acidification effects due to the lowest pH at deeper oceanic depths as well as limitations to migration (Hauri et al., 2009). Red abalone create their shells out of aragonite, a soluble form of calcium carbonate ($CaCO_3$), through the process of biomineralization which is negatively impacted by lower oceanic pH and varies with intensity through different life stages. Specifically, studies have found that survivorship is lower for larval red abalone when exposed to acidified seawater and thermal stress, particularly at the pre-torsion and late-veliger stages of larval life; however, expression of genes responsible for biomineralization were unaffected (Zippay and Hofmann, 2010). Although increasing ocean acidification is likely to impact red abalone, particularly during vulnerable larval stages, combinations of environmental stressors that are likely to increase as temperatures rise, pose a larger threat to the red abalone population.

b. Hypoxia

Hypoxia, or low oxygen zones are common in nearshore marine waters particularly during summer months when upwelling is increased, bringing deeper low oxygen water to the surface. As ocean circulation patterns are thought to be changing in conjunction with climate change, hypoxic events are likely to become more frequent and longer in duration (Gobler and Baumann, 2016).

Low oxygen zones are most likely to impact larval and juvenile stages of red abalone, with laboratory studies finding that prolonged exposure to low oxygen levels results in increased mortality for juvenile red abalone (Kim et al., 2013). However, high variation in growth rates under low oxygen and decreased pH has suggested cryptic phenotypic plasticity among red abalone. Recent genetic studies have investigated this phenomenon by comparing genes that regulate oxygen levels in red abalone and have suggested that localized adaptation to hypoxia is occurring throughout their range (de Wit and Palumbi, 2013; Kim et al., 2013).

c. Climate Change

In addition to changes in ocean chemistry, there are a number of other potential impacts of a changing climate on nearshore marine habitats and species. These impacts include increasing ocean temperatures, sea level rise, changing nutrient availability, increased storm intensity, and altered circulation patterns including changes to upwelling and stratification. These physical changes, in turn, may alter biological processes through shifts in species ranges, invasions and local extinctions, and ecosystem regime shifts (Brierley and Kingsford, 2009).

Growth models of red abalone have been explored in California, and hierarchical models which can account for growth variability have suggested that increasing sea surface temperatures (SST) will result in slower growth rates(Jiao et al., 2010). Lowering growth rates could also be caused by decreased kelp densities. Warmer temperatures may also cause lower food availability, reduced reproduction rates, and increased disease (Boch et al., 2017; Brierley and Kingsford, 2009; Gobler and Baumann, 2016; Leighton, 1974; Rogers-Bennett and Catton, 2019). Accounting for increased SST and its impacts on red abalone growth will be an important variable to monitor when considering fishery models and management as ocean conditions change.

d. Diseases

Few diseases affect the health of wild red abalone populations, with most diseases exclusively affecting aquaculture production, but one known threat to wild abalone populations could increase as environmental conditions continue to change in the marine environment. Withering foot syndrome, is caused by the intracellular bacterium *candidatus xenohaliotis californiensis* and infects the gut tissue of red abalone. The main side effect of this syndrome is a shrunken foot muscle which affects mobility, substrate attachment and overall gut health (Crosson et al., 2014). Although southern California red abalone populations have been found to be severely affected by this disease, northern California populations experience lower water temperatures and therefore have fewer bacteria. Oregon red abalone population occupy very similar conditions to northern

California (Crosson et al., 2014; Moore, 2002). As sea surface temperatures rise, increased withering foot syndrome cases are expected to be present as more bacteria can grow.

e. Ecological Changes

As environmental conditions continue to shift causing complications and cascading effects in the rocky nearshore environment, consideration should be given to the ecological changes which are affecting the red abalone population in Oregon. Specifically, physical changes to the environment (described in the changing ocean conditions and climate change sections above) may have increasing effects on biological interactions including range shifts, local extinctions, shifting dynamics, food availability and predator-prey interactions. Organism dispersion, presence and increases that would affect or have already affected the red abalone in Oregon are pinto abalone (*Haliotis kamtschatkana*), the green sea urchin (*Strongylocentrotus droebachiensis*) and purple sea urchin (*Strongylocentrotus purpuratus*). Although the biogeographic range of pinto abalone is from southeast Alaska to Point Conception, CA (Geiger, 1999), they are rare in Oregon. However, pinto abalone have recently been found more frequently in Oregon waters by sea urchin divers and during sea urchin surveys (Scott Groth pers. Comm.).

In addition to increasing competition for food and space, the disappearance of predators in the rocky nearshore environment is of high concern, in relation to the red abalone. Purple sea urchins are preyed upon in the subtidal and intertidal environments by large soft bodied predatory sea stars which have effectively disappeared from the environment. Sea Star Wasting Disease (SSWD) has decimated populations of *Pycnopodia helianthoides* in Oregon. Without this predator, purple sea urchins outcompete red abalone for both kelp and space. In 2020, the sunflower star (*P. helianthoides*) was classified as critically endangered on the International Union for Conservation of Nature (IUCN) red list, and efforts are underway to solve this problem(Gravem et al., 2021).

f. Re-introduction of Sea Otters

In Oregon, sea otters have been absent since their extirpation by hunting in the early 1900s (Jameson, 1974). Currently re-introduction of sea otters to Oregon is being considered. Sea otters prey on benthic invertebrates, with preference for abalones and sea urchins. The effect of introducing sea otter populations into an area that was previously unoccupied is documented for central California (Hines and Pearse, 1982; Watson, 2000; Wendell, 1994). Although sea otters are thought to stabilize abalone populations through predation pressure which leads to behavioral and physiological shifts, the red abalone population in Oregon could be uniquely affected by this re-introduction. Hines and Pearse 1982 found that larger red abalone in their study site were removed by sea otters and were not protected by refugia in crevices. An important consideration for the red abalone resource in Oregon is the nature of the recreational fishery as a trophy fishery, with a fishery mean size of 245 mm SL, potentially indicating that the re-introduction of sea otters would diminish large red abalone in Oregon. Removing large red abalone from the environment could diminish reproduction due to the increased reproductive output of large red abalone (Rogers-Bennett et al., 2007; Rogers-Bennett and Kashiwada, 2004; Rogers-Bennett and Leaf, 2006). Fisheries for abalone and resident populations of sea otters have been shown to be mutually exclusive (Hines and Pearse, 1982; Watson, 2000; Wendell, 1994). A sea otter reintroduction in Oregon would likely require permanent closure of the red abalone fishery and increased monitoring for population conservation concerns.

v. Sustainable Harvest Levels

Our understanding of sustainable harvest levels for the red abalone population in Oregon is weak and mostly draws on fishery dependent data. Recreational red abalone permit data from the 1970s demonstrates that harvest was low. Specifically, permit data from 1973-1979 reported an annual average of 28 abalone caught, comparatively, between 1996-2017, annual average catch increased to 145 red abalone. Reported take peaked in 2017, with 299 red abalone caught (Groth and Smith, 2022). As population data varies and is always moving, annual catch can change based on fishing and environmental pressure.

Future sustainable harvest levels would be very low (aka *de minimis*). Levels should be adjusted to lower than 50% of historic peaks or based on new survey information. Implications for management and recommendations are explored in the recommended actions section.

vi. Information Gaps and Research Needs

More information about the red abalone population in Oregon is needed to further understand the dispersion, health, and viability. In addition to fishery management criteria, conservation is a priority of this framework and ODFW. This section outlines the information gaps and research needs for effective conservation and management of red abalone in Oregon.

a. Stock Assessment

An important metric for determining management and conservation practices and limits for a species is understanding how to quantify abundance, dispersion, and connectivity. Due to difficulties in red abalone life history and access to their habitat, established stock assessment methods have not been established for Oregon. Quantifying red abalone abundance through adaptive methodologies, determining population trends and number of spawners is needed to accurately assess the status of red abalone in Oregon. Further studies and surveys focused on determining metrics for consistent monitoring and setting limits for biological resilience are important for future management and conservation considerations.

b. Recruitment Variability

Red abalone recruitment drivers are not well understood, but it has been shown to vary based on local environmental and biological conditions. Studies on red abalone in California have shown that in the south, they can spawn twice a year, in the central areas they can spawn year-round and in the north spawning peaks in April through July in conjunction with the spring algal bloom (Ault, 1985; Ault et al., 1985; Hart et al., 2020; Price, 1974). In Oregon, there have not been studies to determine when spawning occurs, and it is thought that the variable nature of the environment and low number of individuals could lead to low recruitment levels such as the "black hole sink" phenomenon, described by (Holt and Gomulkiewicz, 1997). This would mean a subpopulation or cluster could receive all recruits from a geographically separate "source" and it does not provide genetic information as a "sink" population (Gomulkiewicz et al., 1999; Holt et al., 2003; Holt and Gomulkiewicz, 1997). However, further studies focused on determining when seasonal recruitment in Oregon would help to understand recruitment. The proposed management strategy for northern California's red abalone fishery is based on quantifying successful reproduction through Spawning Potential Ratios (SPR) this would be a useful metric for Oregon as well.

c. Climate Change

Ocean conditions are changing, and the impacts of ocean acidification, hypoxia and increased temperature changes are expected to impact marine organisms and accelerate in the future.

Research indicates that changing conditions are likely to affect the dispersion and productivity of red abalone, but quantitative estimates are lacking. Understanding climate sensitivities of red abalone and incorporating into monitoring would aid management in adapting to these changes.

d. Larval Dispersal

Since adult abalones are known to move little (Bonnot, 1948; Cox, 1962; Hines and Pearse, 1982), larval dispersal is likely to be the primary mechanism for the dispersion of the species. Movement within and between populations is a key component in understanding red abalone stock structure. Few studies have looked at larval movement, behavior, and dispersion for red abalone (Mccormick et al., 2012; Rogers-Bennett et al., 2016; Watson et al., 2010), and none have determined the pattern of dispersal and movement for red abalone in Oregon. Knowing how Oregon red abalone disperse over a temporal scale would allow managers to understand the source/ sink dynamics guides the valuation of components of the metapopulation.

e. Natural Mortality

Few studies have investigated natural mortality (M) of red abalone, and none have addressed natural mortality in Oregon. (Rogers-Bennett et al., 2007) found that red abalone are slow growing with low to intermediate natural mortality rates ranging from 0.11 to 0.23 y^{-1}. Natural mortality is a parameter used when considering biologically sustainable harvest levels, known to vary widely across a species range. While we could apply M calculated for northern California red abalone to Oregon, a more localized estimate would be useful to apply to biological reference points, key to conservation and management.

f. Marine Mammal Interactions

Currently there are no known marine mammal interactions that affect Oregon's red abalone. However, recent considerations to re-introduce sea otters would likely have a major impact on red abalone populations. If sea otter re-introduction does occur, examination of the red abalones' population viability should be a high priority.

C. Management and Conservation Strategy

This Management and Conservation Strategy articulates the practices and goals for the red abalone stock. Related goals and objectives are defined considering ecological and socioeconomic aspects of the utilization of red abalone. A description of management practices and current issues facing the fishery is provided and followed by an evaluation of available management tools.

i. Management Approach

Prior to the suspension of the red abalone recreational fishery in 2018, the management approach for red abalone in Oregon was simplistic. Using minimum legal size (MLS), a reporting permit, daily and annual catch limits constrained total catch but did not account for environmental or population density changes.

Here, explicit management goals and objectives are suggested for a more careful/advanced management/conservation strategy for the future.

The future goals of red abalone management should meet explicit biologically informed reference points, incorporate flexibility with respect to ecological shifts and consider the implications for social and economic impacts.

a. Management Goals

The management goals described in this strategy apply to red abalone harvested recreationally in Oregon waters. The identified goals reflect long-term desired outcomes for the Oregon red abalone fishery, coastal communities, and larger ecosystem. These include:

1. **Ecological** – Ensure the long-term reproductive capacity and health of the red abalone population, minimize impacts to other species, and support ecosystem health.
2. **Social/cultural** – Promote diverse opportunities for present and future generations to use, enjoy, or harvest the red abalone resource.
3. **Economic** – Support the economic importance of red abalone in Oregon through education, conservation, and potential fishing opportunities.

b. Management Objectives

To accomplish these goals, there are specific objectives that will be re-evaluated in subsequent revisions of this plan.

Management objectives include:

Ecological

- **1.1** Develop and implement management strategies that maintain red abalone at or above the levels necessary to ensure species and ecosystem productivity.
- **1.2** Develop and implement management measures that prevent serious or irreversible harm to the key elements of ecosystem structure and function, and

that support ecosystem structure, function, and resilience to changing climate and ocean conditions.

1.3 Conduct periodic reviews of the best available information on the biological status of the resource and impacts of the fishery to inform management decisions.

Social/cultural

2.1 Maintain, develop, and implement management measures that consider the cultural and aesthetic value of the red abalone fishery and species in Oregon.

2.2 Provide access to either harvest or enjoyment of red abalone that ensures harvest sustainability and considers the needs of recreational users.

Economic

3.1 Develop and implement management measures that optimize long-term harvest from the red abalone fishery and, to the extent possible, minimize adverse economic impacts on coastal communities.

3.2 Support coastal tourism by creating red abalone enjoyment opportunities, considering the non-consumptive economic value of red abalone in Oregon, and providing a framework for future fishing opportunities.

Considerations for Implementing Objectives

c. Interstate Management Approaches

Regulations that are passed in one state have the potential to impact fishing effort or activity in adjacent states. For example, several of Oregon’s key regulations addressing recreational red abalone fishing in Oregon are in response to data, experiments and regulations explored and passed in California. Although rules are adopted in each state through independent processes, the regulations and management structure are generally consistent; however, there are several key differences among the regulatory processes in these two states which impact coastwide red abalone management.

a. Oregon

Oregon's abalone fishery is governed by a series of Oregon Revised Statutes (ORSs) that are adopted or modified by the Oregon Legislature, and Oregon Administrative Rules (OARs) that are adopted or modified by the Oregon Fish and Wildlife Commission. The OFWC (established under ORS 496.090) consists of seven governor-appointed commissioners who are charged with setting policies and developing general state programs that provide for the productive and sustainable management and utilization of fish and wildlife resources by all user groups. Implementation of both ORSs and OARs is overseen by ODFW with enforcement functions carried out by the Oregon State Police.

b. California

Regulations related to recreational abalone fishery management in California are adopted by the California Fish and Game Commission in the California Code of Regulations. The California Fish and Game Commission is comprised of five governor-appointed members broadly charged with ensuring the long-term sustainability of California's fish and wildlife resources. Enforcement and implementation of regulations for the recreational red abalone fishery is performed by CDFW.

California has suspended their recreational red abalone fishery until 2026(Taniguchi and Traverso, 2021). Currently, an integrative management plan is in progress, with many of the proposed management strategies referenced in this plan, utilizing information provided in the Management Strategy Integration Process final report (Jackson et al., 2020). Management of the recreational red abalone fishery in California is divided into fishery zones that encompass different geographical areas, each that has its own total allowable catch (TAC).

ii. Conservation Approach

Previous management of the red abalone resource in Oregon has been conservative and reactive, through monitoring of the stock and catch metrics. However, as ocean conditions continue to change and impact red abalone populations, a shift towards a proactive and precautionary approach could be more effective. This conservation approach serves as a guideline in the absence of a fishery for appropriate conservation of the red abalone resource in Oregon, as well as a framework for continuing to support the possibility of a fishery should environmental and biological conditions allow.

a. Conservation Goals

The conservation goals described in this strategy apply to red abalone in Oregon waters. The identified goals reflect long-term desired outcomes for the Oregon red abalone population and health of the larger ecosystem. These include:

1. Monitor the red abalone population in Oregon.
2. Increase understanding of the stock.
3. Allow for recovery of the red abalone population in Oregon.

4. Diminish competition for food and space in the marine environment.

b. Conservation Objectives

To accomplish these goals, there are specific objectives that will be re-evaluated in subsequent revisions of this plan.

Conservation objectives include:

1. Monitoring

1.1. Conduct fishery independent surveys at two sites biennially.

1.2. Evaluate monitoring strategies through assessment of non-traditional and adaptive methodologies to determine efficacy and cost effectiveness of consistent monitoring.

2. Stock status

2.1. Utilize the best available science to determine population dynamics.

2.2. Perform genetic analysis for the structure of the red abalone population in Oregon.

3. Recovery

3.1. Eliminate fishing pressure for red abalone populations in Oregon until metrics for recovery are established.

3.2. Consider feasibility and need for enhancement efforts for red abalone populations in Oregon.

4. Competition

4.1. Monitor kelp densities in Oregon with special consideration for kelp beds that support red abalone populations.

4.2. Reducing high levels of competition for space and food by culling purple sea urchins in areas with red abalone present.

<u>iii. State Authority</u>

The red abalone resource in Oregon is managed at the state level by the Oregon Department of Fish and Wildlife.

<u>iv. Oregon Red Abalone Fishery Description</u>

The red abalone fishery in Oregon has only been recreational since the closure of the exploratory commercial fishery in 1962. Here we describe the history of both the recreational red abalone fishery in Oregon and the exploratory commercial fishery in Oregon as well as entities involved in management and conservation that must be considered when creating the future regulation of the red abalone resource.

a. Fishery Sectors

a. Recreational Fishery

Oregon's recreational fishery for red abalone began in the early 1950s, with increasing interest and harvest leading to adoption of initial rules in 1959. A catch report permit was introduced in 1973, but not required for harvest until 1996. Few rule changes have been made to the fishery since its inception in 1959, in response to concerns regarding the population and environmental conditions associated with red abalone.

b. Exploratory Commercial Fishery

A short exploratory commercial fishery for red abalone persisted from 1958-1962 focused on determining more information about Oregon's red abalone stock and if a commercial fishery was feasible. In 1962, following limited harvest and decreasing project momentum, the contract with divers was terminated citing a higher need for conservation rather than commercial harvest (Snow, 1962).

b. Entities Involved in Management

In the 1950s through 1970s, fish and wildlife regulation in Oregon was accomplished through separate Fish and Game Commissions which were periodically reorganized to keep pace with increasing interests in game and game fish and shifting priorities. In 1975, the separate State Wildlife Commission and State Fish Commission were integrated into a single Department of Fish and Wildlife overseen by a State Fish and Wildlife Commission. Today, the following entities have a legal role in the management of the red abalone resource in Oregon.

a. Oregon Department of Fish and Wildlife

The Oregon Department of Fish and Wildlife (established under ORS § 496.080) is the executive branch of state government responsible for managing Oregon's fish and wildlife and their habitats. ODFW is authorized in statute by the state Legislature and in administrative rule by the OFWC, to administer the regulation and management of Oregon's commercial and recreational fisheries.

ODFW implements this authority for Oregon's red abalone fishery through the Marine Resources Program within the agency's Fish Division. The MRP carries out state management actions through work focused on three main categories:

1. Marine resource management, policy, and regulation
2. Monitoring and sampling of marine fisheries
3. Research and assessment of marine fisheries, species, and habitats

MRP staff represent Oregon as members of numerous groups which coordinate interstate fishery management processes, such as the Pacific Fishery Management Council and the Pacific State Marine Fisheries Commission.

b. Oregon State Legislature

Statutes (i.e., ORSs) are created and passed by the Oregon Legislature. The Oregon Legislature also appropriates and allocates funding on a two-year (biennial) budget cycle to all state agencies, including ODFW. Legislative approval for ODFW's staffing and budget has generally been stable or growing since the late 1990s, including staffing and funding appropriated to the MRP.

c. Oregon Fish and Wildlife Commission

The Oregon Fish and Wildlife Commission (established under ORS 496.090) consists of seven governor-appointed commissioners who are charged with setting policies and developing general state programs that provide for the productive and sustainable utilization of fish and wildlife resources by all user groups.

d. Oregon State Police

The Oregon State Police play a key role in supporting ODFW's mission as the single entity tasked with enforcement of fish and wildlife regulations. Within the OSP Fish and Wildlife Division, seven troopers and a sergeant are assigned to a Marine Fisheries Team that is responsible for coastwide enforcement of commercial and recreational fishing regulations.

ODFW and OSP use cooperative enforcement planning as a tool to set enforcement priorities for each species. Personnel from each agency meet annually to discuss priority issues and objectives so that cooperative enforcement plans (CEPs) can be developed. This ensures that enforcement efforts are in line with ODFW's management priorities and goals. OSP also works collaboratively with other enforcement entities (NOAA enforcement, the USCG, WDFW, and CDFW) through the PFMC process.

e. Oregon Department of Agriculture

The Oregon Department of Agriculture (ODA) regulates natural resources which are harvested for human consumption. ODA samples and tests various shellfish that might harbor bacteria or harmful diatoms that could impact human health. Red abalone in Oregon have not been impacted by harmful bacteria that have caused diseases such as Withering Syndrome (WS) in past years. However, as ocean conditions continue to shift to warmer temperatures, ODA could become more involved in testing red abalone for bacteria if re-opened for human consumption.

f. Department of State Lands

The Oregon Department of State Lands (DSL) regulates two important factors that influence the red abalone resource in Oregon. Subtidal and intertidal rocks, which act as substrate and essential habitat for red abalone, and kelp, the main food source for red abalone, are managed by DSL.

c. Other Entities

The red abalone fishery has always been managed by the state, but other entities have been and are currently involved in management processes.

a. Research Institutions

ODFW partners with a variety of researchers and natural resource professionals from different institutions to expand research and monitoring efforts that are critical to informing effective management of Oregon's fishery resources. This conservation and fishery management plan is the result of a collaboration between ODFW, Oregon Sea Grant and the University of Oregon.

d. Fishing Method and Gear

Three fishing methods for red abalone in Oregon have been utilized by fishery participants, including: 1) SCUBA (Self-Contained Underwater Breathing Apparatus), 2) free dive and 3) shore pick. Catch report permits indicate that the majority of red abalone fishing is performed by SCUBA diving (51.4 % of users), followed by free dive (29.3% of users) and lastly shore pick (19.2%).

Fishery participants are required to premeasure red abalone prior to removing the animal from substrate to ensure minimal damage to undersized red abalone. The use of an abalone iron for removal and caliper for measurement is a common practice.

e. Season Opening

There has not been a defined season for red abalone fishing in Oregon. Future managers might consider limiting the season to protect potential spawning months.

f. Summer Fishing and Season Closure

Oregon's recreational red abalone fishery has not been restricted by season historically. However, due to diving and weather conditions in Oregon, abalone fishing has been limited based on environmental factors. In California, the red abalone fishery was closed for the month of July to allow for spawning to take place without fishing pressure, as well as December through March. Future management regulations could implement a seasonal closure for spawning or have a limited number of fishing days to regulate take.

g. Social and Economic Components

a. Recreational Fishery Economic Contribution

Recreational red abalone fishing in Oregon is a unique opportunity for participants and has grown in popularity with divers worldwide, though the economic contribution of the red abalone fishery in Oregon has not been quantified. For northern California, an estimated 10 million USD in annual direct expenditures, and over 17 million USD in final output for local economies (California Department of Fish and Game, 2005) has been suggested. Oregon's red abalone fishery has had an average of 175 issued permits in the last ten years (1996-2017), compared to an estimated 200,000 participants in the northern California fishery.

b. Non-consumptive Value

Red abalone have direct consumptive value through their harvest, but also have non-consumptive value in which their existence in the ecosystem and for future use holds value. Non-consumptive value refers to functions or services of a natural resource in an ecosystem, and the preservation of red abalone in Oregon has value for future use and enjoyment (Walpole and Thouless, 2005). Integrating the non-consumptive use of abalone has been applied to South African fishery policy (Crookes, 2016; Nielsen and Martin, 1996) could be considered for red abalone management in Oregon.

v. Current Issues

There are several prominent issues currently facing the red abalone resource and fishery in Oregon. Some of these present complex management challenges that are active areas of research and discussion.

a. Climate Change

A full description of the changing ocean conditions and the potential effects to red abalone, including ocean acidification, hypoxia and climate change can be found in the information gaps and research needs section. Monitoring changing ocean and climate conditions will be critical to achieving management and conservation goals for the red abalone in Oregon.

b. Sea Otter Re-introduction

The pacific sea otter was once a prominent part of the marine subtidal ecosystem in Oregon, but since their extirpation by hunters in the early 1900s, the ecosystem has changed in their absence. In the case of red abalone, behavioral changes that shape the health and structure of wild populations are a side effect of the absence of sea otters. Without sea otters present, red abalone exhibit emergent behavior in which abalone do not solely occupy rock crevices, but instead emerge out into the subtidal and even up into the intertidal (Hines and Pearse, 1982; Watson, 2000). This effect is exacerbated by lack of kelp, forcing red abalone to forage, and eliminating their cover from potential predators (Rogers-Bennett and Catton, 2019). The re-introduction of sea otters to the southern Oregon coast would threaten the remainder of the red abalone population in Oregon, without allowing time for adaptation to cryptic behaviors.

As plans to discuss and implement the re-introduction of sea otters continues to progress, it is important for both management and biological considerations of the red abalone population in Oregon to be considered and addressed.

c. Population Concerns

As populations of red abalone throughout their range are suffering from declines and health issues, quantifying population levels is of increasing importance. In Oregon, specifics about population structure and size are still largely unknown and it is difficult to determine fishery possibilities and metrics without understanding the stock confidently. Increasing understanding of the stock and monitoring changes both environmental and biological will be critical for both management and conservation goals of the red abalone in Oregon.

vi. Other Social and Cultural Uses

Red abalone are an important social and cultural component of the south coast of Oregon. Documentation of abalone use by both indigenous peoples and later European settlers is minimal in the coastal Pacific Northwest, even further limited for the southern Oregon coast. However, ODFW documentation provides information regarding use of red abalone through fishery regulations in the 1950s (McCauley, 1953). This resource has remained an important part of the southern Oregon region socially, culturally, and economically. Investigations to determine the source of red abalone use in indigenous communities in Oregon have hypothesized that red abalone shells, used for decoration and ceremonial applications, were acquired through trade (Zobel, 2002). Earlier documentation suggests that red abalone shells were brought to the Pacific Northwest tribes through trade from Monterey, California where red abalone were plentiful and their use in California tribal communities is well documented(Bonnot, 1948; Heizer, 1940; Leechman, 1942).

As red abalone remain an integral part of both southern Oregon social and cultural communities, it is an important consideration when creating management and conservation regulations.

vii. Biological Reference Points

Reference points have been suggested as effective ways to take a precautionary approach to management of fisheries in recent years (Caddy and Mahon, 1995). Further work by the Food and Agricultural Organization (FAO) focused on applying defined reference points (RP)s to management with particular interest in data-poor situations, which may require empirical RPs with a number of options to be evaluated and adapted through time (Caddy, 1998). Suggestions for defining these RPs for the recreational red abalone fishery in Oregon are presented below, accompanied by potential adaptive management considerations if RPs are reached.

Prior to the emergency closure and suspension of the recreational red abalone fishery in Oregon in 2018, there were no limit reference points in place to trigger a closure or suspension.

Recommended LRPs for Oregon are as follows:

1. Recreational red abalone fishery in northern California is closed.
2. Densities drop below 0.03 red abalone per m^2 at either site.
3. Purple sea urchin (*Strongylocentrotus purpuratus*) densities are not considered a threat to red abalone population viability.
4. Bull kelp (*Nereocystis luetkeana*) densities do not limit red abalone population viability.

LRPs are limits that will alert management to consider changing Harvest Control Rules (HCR)s. If LRPs are reached, ODFW will determine adaptive management strategies and conduct research to address concerns.

The red abalone fishery in Oregon is currently suspended until 2024 (Rumrill, 2021). Should a fishery be established, suggested adaptive management actions in response to LRPs are presented below.

An adaptive management response may involve management actions including:

1. **Fishery closure**
    - Closing the fishery until more information is acquired or density levels meet targets will allow for more information to be acquired and eliminate fishing pressure on the population.
2. **TAC reduction**

- Develop TAC
- Reductions in the Total Allowable Catch (TAC) could be a consideration when deciding how to minimize impacts on the population and environment.

3. **Site closure**

- Define sites
- There are two proposed sites for the Oregon red abalone fishery (Brookings and Port Orford) based on survey data. Closing a site if LRPs are reached could be a consideration if differences in site densities differ.

viii. Evaluation of Management Tools

The management tools utilized in the Oregon red abalone fishery are a minimum legal size (MLS), daily and annual limits, required pre-measurement of red abalone, and submission of catch report permit. These tools are commonly use in abalone fisheries worldwide due to enforcement ability and biological understanding; however, they have not always been successful in limiting catch rates or effects of harvest on reproduction and abundance. Here, we evaluate each management tool for consideration in future strategies.

Management Tool: Minimum Legal Size (MLS) of 203 mm (8 inches)

The use of a MLS in abalone fisheries is common and often allows reproductively immature abalone to be protected from removal. In the case of red abalone in Oregon, the MLS of 8 inches (203 mm) did little to govern catch size due to the nature of the fishery. As a trophy fishery, participants target larger red abalone almost exclusively with the mean fishery catch size being well above the MLS at 254 mm (10 inches). A minimal increase in MLS would likely not have a meaningful impact on the harvest of red abalone in Oregon; an increase to 11 inches (279 mm) could reduce catch rates and could be a consideration for alternative management options.

Management Tool: Daily and Annual limits (1/day, 5/year)

Daily and annual limits are useful for enforcement purposes, allowing catch rates to be limited and enforced. Although daily and annual limits can be useful for fishery management, they require a denominator as a basis for setting limits. In the case of the red abalone fishery in Oregon, a discrete number of allowable harvest in the form of a total allowable catch (TAC) with a limited entry system could be more appropriate.

Management Tool: Required pre-measurement

Required pre-measurement of red abalone is appropriate in a fishery with an effective MLS in place. A larger MLS may be sufficient to increase effectiveness of proposed management tools.

Management Tool: Catch report permit

Catch report permits are useful for understanding and reporting the amount of take in a fishery, as well as location information. Catch report permits could be considered as a minimum requirement for biological and spatial information when setting new management protocols.

ix. Recommended Actions

Through understanding of the biology, ecology, available data and threats to the red abalone resource, a comprehensive conservation and fishery management strategy can be established for present and future managers to consider. Sections are divided up into conservation measures and management recommendations if a fishery is determined to be possible.

a. Conservation Measures

Proposed conservation measures are organized by conservation goals and objectives for the red abalone resource in Oregon.

1. **Goal**: Monitor the red abalone population in Oregon.

Objective: Conduct fishery independent surveys at two sites biennially.

Measures:

1.1 Seek funding for surveys.

1.2 Create a monitoring program.

1.3 Support current personnel to organize surveys.

1.4 Create a position to conduct surveys.

1.5 Consider collaboration with former divers or academics

Objective: Evaluate monitoring strategies through assessment of non-traditional and adaptive methodologies to determine efficacy and cost effectiveness of consistent monitoring.

Measures:

1.6 Conduct survey methodology evaluations.

1.7 Contract divers to conduct density surveys comparing methods.

2. **Goal:** Increase understanding of the red abalone stock.

Objective: Utilize the best available science to determine population dynamics.

Measures:

2.1 Support performing age studies on red abalone in Oregon to develop an age-at size estimation.

2.2 Seek funding or collaborate with researchers to perform larval dispersion studies for further understanding of life history strategies of red abalone and dispersion in Oregon.

Objective: Perform genetic analysis for the structure of the red abalone population in Oregon.

Measures:

2.3 Seek funding for genetic analysis to determine number of spawners.

2.4 Seek funding for genetic analysis to determine genetic diversity.

3. **Goal:** Allow for recovery of the red abalone population in Oregon.

Objective: Eliminate fishing pressure for red abalone populations in Oregon until metrics for recovery are established.

Measures:

3.1 Extend fishery closure until LRPs are met.

3.2 Alter fishery regulations to support recovery of red abalone in Oregon.

4. **Goal:** Diminish competition for food and space in the marine environment.

Objective: Monitor kelp densities in Oregon with special consideration for kelp beds that support red abalone populations.

Measures:

4.1 Perform spatial kelp surveys at sites where red abalone populations are present biennially.

4.2 Seek funding or collaborate with researchers to survey kelp beds at fished sites.

Objective: Eradicate high levels of competition for space and food by culling purple sea urchin populations in areas with red abalone present.

Measures:

4.3 Partner with constituents to reduce purple sea urchin populations at historically present sites.

4.4 Seek funding for further sea urchin monitoring and culling efforts.

4.5 Support restoration of *Pycnopodia helianthoides* presence in Oregon.

b. Management Recommendations

The red abalone population in Oregon is imperiled and does not appear able to sustain a fishery. The recommended conservation goals, objectives and measures listed in this plan are designed to support red abalone recovery to ensure the propensity of the resource for present and future generations. Should conservation measures be applied and prove effective, LRPs can be assessed to determine if fishery is possible. Below are potential management implications for a red abalone fishery in Oregon, listed as options with varying strategies and implications.

a. Option 1: De minimis Fishery

In the event that the recommended LRPs are not exceeded, a *de minimis* fishery could be possible for red abalone in Oregon.

A *de minimis* fishery would allow minimal catch; proposed regulations for this fishery are:

1. The red abalone fishery operates in two designated sites: Brookings and Port Orford, defined by extents of fishery independent surveys

2. A total allowable catch (TAC) for all sites combined is set based on historic catch rates and survey densities, not to exceed 50% of the average of catch for the last ten years the fishery was open (2008-2018).

   a. 50% of the last 10-year average of catch (2008-2018) is 70 red abalone.

   b. Site-specific catch is designated by historic percentage, as 97% of historic red abalone catch has occurred in Brookings, 97% of the TAC for the state of Oregon will be allocated to the Brookings site.

      i. TAC by area would not exceed: 68 (Brookings), 2 (Port Orford).

3. Surveys for fished sites will be performed biennially to ensure densities are above previous baseline densities of 0.03 red abalone per m^2.

4. 70 permits can be issued, with one red abalone allowed per permit holder annually.

5. Permits will be issued based on a lottery system.

6. If LRPs are exceeded, all sites will close immediately.

b. Option 2: Alternative Fishery

An alternative to a *de minimis* fishery if LRPs are not met, but a fishery is desired, is a small fishery focused on collecting biological information (aka bio-fishery) could be developed.

Regulations for a proposed alternative fishery are as follows:

1. 5 red abalone are allowed to be harvested annually.

2. Permits could be issued based on a lottery system, with one permit issued for each red abalone allowed to be harvested (5 permits total).

3. Harvesters would work with ODFW to obtain needed biological sampling.

c. Option 3: Status Quo

A third option for management would be to re-open the recreational red abalone fishery when LRPs are met with status quo rules. This option would be appropriate if the need for red abalone fishing opportunities exceed the conservation needs.

Regulations for an open fishery are as follows:

1. Minimum legal size (MLS) of 8 inches 203mm SL.

2. Daily limit of one red abalone per permit holder.

3. Annual limit of five red abalone per permit holder.

4. Required pre-measurement of red abalone.

5. Reporting requirement.

Red Abalone Fishery Management Implications

Adaptive management is fundamental to ODFW's approach to addressing several current issues. Each fishery option utilizes a different fishery management strategy and has varying implications for the red abalone population in Oregon.

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