

Black Abalone & Sedimentation
Literature Review
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Prepared for:
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Introduction

Black abalone (*Haliotis cracherodii*) are a large marine snail (Phylum: Mollusca, Class: Gastropoda, Subclass: Vetigastropoda, Family: Haliotidae) which inhabit the rocky intertidal, or the area between the high tide and the low-tide marks (Cox 1962). Their range extends along the west coast of the United States from Baja California up to mid-Oregon, as well as on the Channel Islands and Farallon Islands off the coast of California (NOAA Fisheries, CDFW 2001, Cox 1962). Abalone find protection deep in rock cracks and crevices in the intertidal zone, and primarily feed upon diatomic algae and fragments of surfgrass that drift into their rock crevices (Cox 1962, Leighton & Booloottian 1963). *H. cracherodii* populations are highly variable throughout their existing range, and are often concentrated in areas of suitable habitat (Raimondi et al. 2002). Black abalone maintain their grip on the rocky substrate with a muscular foot and are protected by a thick dark blue/green shell which can grow up to 20 cm in length on adult individuals (NOAA Fisheries). The growth rate of black abalone is generally quite slow, and observed to proceed at an irregular rate over individuals within the species, depending mainly upon the consistency of food availability throughout the year (Cox 1962). Predators of *H. cracherodii* include sea stars (*Pisaster spp.*), spiny lobsters (*Palinuridae spp.*), octopus, fish such as the California sheephead (*Semicossyphus pulcher*) and cabezons (*Scorpaenichthys marmoratus*), and sea otters (*Enhydra lutris nereis*) (Cox 1962, Raimondi et al. 2002).

Black abalone are an incredibly resilient species. While other species of abalone live below the low tide line in calmer waters, *H. cracherodii* have evolved to withstand the constant movement of tide shifts and battering ocean waves in the energetic intertidal zone. Black abalone depend upon the drifting current not only to provide them with a food source, but for reproduction as well. Black abalone are dioecious broadcast spawners, meaning that they release their eggs and sperm into the water when environmental conditions are right, and must have a population of close proximity to ensure fertilization (Cox 1962, Miner et al. 2006). Research suggests that a crucial part of the abalone recruitment process is a dense aggregation of fecund adult individuals, because successful abalone spawning is confined to localized dispersal, where fertilized larvae primarily settle in an area close to their parents (Miner et al. 2006, Tegner et al. 1996).

Native tribes such as the Island Chumash have harvested abalone from the rocky coast of the Channel Islands since time immemorial (Chumash Ecosystem Services Assessment 2016). Abalone served as an important subsistence food source to the Chumash, as is demonstrated by the massive shell piles, called middens, which are often located near the shore (Douros 1987, Glassow 2015). These middens are used as archaeological evidence to infer, through radiocarbon dating, the timing of Chumash arrival on the islands, as well as to determine the general size and extent of abalone populations over that time period (Glassow 2015). Local species of abalone have significant cultural value to coastal native communities through their role as a historically traditional subsistence food source, as a focus of community bonding, and as a medium in indigenous art (Chumash Ecosystem Services Assessment 2016). Traditional Ecological Knowledge (TEK) expresses a relationship of intrinsic value and reciprocal and respectful interaction which is invaluable in developing efforts to promote the recovery of an endangered species (Chumash Ecosystem Services Assessment 2016).

“The loss of a species such as white abalone or wild southern steelhead salmon has dramatic cultural significance that transcends mere economic or commercial value for the animal. The ceremonial significance of the animal may also fade in time with the loss of the presence of the animal as a distinct but interdependent part of the greater circle of animals, plants, and insects.”
- Tribal Marine Protected Areas: Protecting Maritime Ways and Practice, 2004

The black abalone population has declined rapidly in recent decades, mainly due to a combination of commercial overfishing, coastal development and habitat loss, and the introduction of a new pathogen causing an infectious disease known as withering syndrome.

Beginning in the 1850s, black abalone were collected by Chinese and Japanese immigrant communities, who took the shellfish from the accessible shallow water and intertidal zone for seafood and bait (CDFW 2001). A large commercial fishery for all California abalone species developed over the successive decades (Alstatt et al. 1996). The epicenter of the fishery gradually shifted farther and farther northward, from southern California to San Francisco, as abalone populations began to decline. Initially, the landings numbers, or recorded take data, was collected indiscriminately of species within the California abalone fishery, meaning it was impossible to keep track of relative species abundance or predict species decline amongst *Haliotis spp.* (CDFW 2001). As other desirable abalone species, such as the pink (*H. corrugata*) and red (*H. rufescens*), declined in number in southern California through the successive decades, the relatively healthy population of black abalone became subject to unsustainable exploitation, especially on the Channel Islands off the coast of southern California (Neuman et al. 2010). A commercial export fishery for black abalone developed in 1968, which mirrored the fisheries of other abalone species in its trend of rapid rise, then sudden steady decline in tonnage (Alstatt et al. 1996, CDFW 2001). Commercial landings for black abalone averaged 290mt in the 1970's, 175 mt in the 1980's, and a meager 14 tons in the 1990's (Neuman et al. 2010). In response to rapidly declining populations, regulations were imposed by The California Department of Fish and Wildlife, and the black abalone fishery was ultimately closed throughout California in 1993.

Withering syndrome

The latest significant threat to black abalone populations is a highly infectious disease known as withering syndrome (WS), which has caused mass mortality along the coast of California in recent decades. Withering syndrome is caused by a pathogen called *Xenohaliotis californiensis*, and is associated with interferences in nutrient absorption in the digestive tract (Richards & Davis 1993). Symptoms of withering syndrome include discoloration of the epipodium and atrophy of the foot muscle, reduced activity and inability to remain attached to the substrate (Alstatt et al. 1996, Neuman et al. 2010). Withering syndrome was first observed in southern California in 1985, where it compounded upon existing population pressures to result in mass mortalities of more than 95% in black abalone populations occurring south of Monterey County, CA (Neuman et al. 2010). Black abalone populations have declined by more than 80% throughout southern/central California since the mid-1970's (NOAA 2020). Mass mortalities attributed to WS are observed as far north as the San Luis Obispo/Monterey County border (Neuman et al. 2010).

“The timing of the initial mass mortalities following the strong 1982 to 1983 El Niño and an isolated outbreak of withering syndrome in 1988 at Diablo Cove, north of Point Conception, following warm water discharge from a power plant, led to the hypothesis that the onset of mass mortalities due to withering syndrome may be triggered by elevated seawater temperatures” - Raimondi et al. 2002 direct quote

The spread and virulence of the disease is suspected to be facilitated by warm spells of ocean temperature, and cooler water temperatures are assumed to prevent the spread of the pathogen and reduce the severity of outbreaks (Richards & Davis 1993, Steinbeck et al. 1992). The recent explosion and pervasiveness of this disease is linked to ocean warming through El Nino events and anthropogenic climate change (Raimondi et al. 2002). To examine the importance of water temperature in WS mortality events, an isolated mass mortality event attributed to WS was observed ~70 km north of Point Conception at the Pacific Gas & Electric’s Diablo Canyon Power Plant in 1998. Black abalone mortalities were observed only in the immediate vicinity of the warm-water discharge point from the power plant, which raised water temperatures to 10°C above ambient temperature (Steinbeck et al. 1992). Outside of the warm water bubble, no black abalone were observed to succumb to WS (Steinbeck et al. 1992).

Mass mortalities associated with withering syndrome are cause for concern. Due to low population densities, recruitment failure and low fertilization success rates are observed in populations of black abalone affected by WS in southern California (Miner et al. 2006, Neuman et al. 2010). These widespread population declines carry worrisome implications for long-term black abalone population dynamics in affected regions (Neuman et al. 2010). The Allee effect proposes the concept of density-dependent reproduction inhibition, describing how occasional recruitment failure in a population may result in a slow decline to extinction when caused by low population density (Allee 1931). With declining numbers of black abalone in isolated pockets along the coast, recruitment failure is now often observed in dispersed black abalone populations, indicating that these populations are unable to recover from a mass mortality event on their own (Miner et al. 2006, Tegner et al. 1996, Neuman et al. 2010). To compound these issues, it is suggested that the presence of adult individuals may maintain suitable habitat for successful recruitment by maintaining cover of crustose coralline algae, clearing the substrate (Miner et al. 2006) and preventing the colonization of other sessile invertebrates such as tube worms (*Phragmatopoma californica*) with which larval and juvenile abalone compete for space (Richards & Davis 1993). It is apparent that without intervention, black abalone face a significant challenge in recovering to healthy population status in the face of continual and combined stressors of wasting disease, a history of overfishing, and habitat loss and degradation.

Regulations and Status Listing

Black abalone are listed as “endangered” under the Endangered Species Act of 1973 (ESA) effective February 13, 2009 (74 FR 1937).

Black abalone are included on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species as of August 2003.

Purpose of report

The purpose of this literature review is to inform rescue operations for black abalone recovery efforts along their range. This report will summarize rescue efforts and the protocol/methodology of a long-term

black abalone translocation program in Big Sur, California, following a massive sedimentation event at Mud Creek in 2017. Important background information will be provided through descriptions of the causes of increased sediment influx into the nearshore aquatic system, seasonal sedimentation cycles and the observed and studied effects of sediment on abalone of all life stages.

Significant sedimentation events

Terrestrially derived runoff can have significant effects on aquatic ecosystems due to its varying physical and chemical properties (Airoidi 2003). A huge sedimentation event such as a landslide can bury critical habitat for *H. cracherodii*, causing mass mortality and habitat loss. Sediment turbidity, deposition and scour are observed to have negative effects on larval settlement, metamorphosis and the long-term health and survival of *H. cracherodii* populations, and therefore poses a significant threat to the survival of this endangered species (Airoidi 2003).

Black Abalone Translocation Manual (2020) - Prepared by: Christy Bell & Dr. Peter Raimondi

On May 20, 2017, the Mud Creek Landslide failed, collapsing the hillside and accompanying Highway 1, just south of Gorda, along the coast of Big Sur, California. Approximately 1500 meters of designated critical habitat for black abalone (*Haliotis cracherodii*) were buried under the heavy sediment flow of boulders, cobbles, and unconsolidated debris, which extended at least 175 m seaward of the original coastline (Warrick et al. 2019). According to the Monterey County Office of Emergency Services report, the Mud Creek slide was caused by heavy winter rains, which loosened the soil on the steep slope above the slide area. Common conditions that lead to a significant landslide event often include drought or a severe fire, which can cause soil to dry up or become hydrophobic, followed by a deluge of water in a heavy rain event, causing a massive runoff of water downslope and ensuing debris flows.

Black abalone experts working with the University of California, Santa Cruz (UCSC) and Monterey Bay National Marine Sanctuary (MBNMS) conducted surveys beginning in July 2017 to determine the extent of the damage and continuing threat that the debris and sediment movement pose to black abalone populations in the area. In the months after the slide, sediment from the settled debris flow began to erode from the site and impact the areas surrounding Mud Creek landslide. A large population of black abalone was identified adjacent to the slide area, and it was determined that the continuing erosion of the settled debris posed a significant risk to the black abalone population at the site. The rate of sediment movement was significant enough to threaten to bury nearby black abalone and their habitat, so by October 2017, experts launched a rescue operation to relocate the black abalone threatened by the aftermath of the slide.

Methods and Recommendations

The methods for launching a black abalone/habitat rescue operation, as elucidated by Christy Bell and Dr. Peter Raimondi in the “2020 Black Abalone Translocation Manual”:

1. Gather historical data and aerial images

Determine if there is a documented population of black abalone in the impacted area. Collect historical data on the health and number of the population(s) to rank or assess cost/benefit of initiating a rescue

operation. Collect historical data on area, and satellite imagery of impacted areas to compare to current conditions and assess the extent of damage to the site.

2. Assess the area impacted or potentially impacted

As soon as possible after a significant sedimentation event, researchers should be deployed to conduct population and habitat surveys to determine current status of black abalone numbers in the area, and characterize existing habitat quality. This data can be compared to historical data of the area (if any). Numbers of live and dead black abalone should be collected over the entire area of concern. To the greatest of their abilities, researchers should identify the size and vulnerability of black abalone in the area to calculate the urgency and extent of a rescue operation.

3. Assess the physical threat to black abalone

Researchers should take careful note to assess the current and potential threat of sediment/debris impacts to black abalone population in the area. The sediment should be scrutinized in its current capacity and in its potential to expand or shift to affect adjacent areas of black abalone habitat. Necessary permits and authorization should be obtained to carry out rescue and relocation operations if necessary, and planning with ample preparatory time to ensure the permits have been approved and are ready when needed. At the Mud Creek Landslide, the sediment was observed to be expanding both upcoast and downcoast of the initial slide site, moved by swell from the ocean. Sediment was shifting into critical black abalone habitat and threatened to bury a large and healthy population that was documented adjacent to the slide.

4. Weigh the risks of moving vs leaving animals in place

Removal and transportation of black abalone is undoubtedly a traumatic and stressful experience for the animals and may result in the death of several individuals. In the next step, it is necessary to weigh the risks of rescue and relocation against the possibly greater loss of black abalone which would be incurred by leaving them in place. Consider that only a small portion of a population will be accessible for rescue, and by rescue it is guaranteed that a portion of the population’s genetic diversity will be preserved as well.

5. Options for moving abalone

The best option is often a combination of those offered here:

- Option 1: Collect and translocate the black abalone directly to another field site
- Option 2: Collect and bring the black abalone into captivity for a short period of time (≤ 24 hours) until conditions (tides) allow for the translocation of black abalone to the chosen field site
- Option 3: Collect and bring black abalone into captivity to monitor their health and conduct phased translocation to the field site
- Option 4: Collect and translocate a portion of the black abalone directly to the field site and a portion to a captive facility or facilities

Table 1: Summary of options for translocating black abalone. Copied directly from Bell & Raimondi 2020. (Table 1, page 18)

Considerations	<u>Option 1</u> : Collect and translocate the black abalone directly to another site	<u>Option 2</u> : Collect and hold in captivity (≤ 24 hr) until conditions (tides) allow for translocation to field site	<u>Option 3</u> : Collect and hold in captivity to monitor health and conduct phased translocation to field site	<u>Option 4</u> : Collect and translocate a portion of the black abalone directly to the field site and a portion to a captive facility
Site Selection	Select nearby site	Select nearby site	Select nearby site	Select nearby site

	outside of impacted area (preferably a MARINE site)	outside of impacted area (preferably a MARINE site)	outside of impacted area (preferably a MARINE site)	outside of impacted area (preferably a MARINE site)
ESA Coverage	Section 7 consultation Section 10 research permit	Section 7 consultation Section 10 research permit Holding included as part of transport and translocation procedures	Section 7 consultation Section 10 research permit Separate authorizations may be needed for collection, holding, and future outplanting	Section 7 consultation Section 10 research permit Separate authorizations may be needed for collection/translocation and for holding/future outplanting
State Authorization	CDFW Permit CDFW Letter of Authorization	CDFW Permit CDFW Letter of Authorization	CDFW Permit CDFW Letter of Authorization	CDFW Permit CDFW Letter of Authorization
Tagging and Processing	Tag Photograph Measure shell length Note injuries Genetic tissue sample	Tag Photograph Measure shell length Note injuries Genetic tissue sample	Tag Photograph Measure shell length Note injuries Genetic tissue sample	Tag Photograph Measure shell length Note injuries Genetic tissue sample
Funding	Personnel (time, travel, equipment)	Personnel (time, travel, equipment) Captive facilities	Personnel (time, travel, equipment) Captive facilities	Personnel (time, travel, equipment) Captive facilities
Personnel	Field biologists	Field biologists Captive facilities	Field biologists Captive facilities	Field biologists Captive facilities
Constraints/ comments	Difficult to complete all tasks in one low tide	Short-term holding allows more time for tagging, processing, and tissue collection	Duration of captive holding with phased translocation plan additional permits needed	Criteria for selecting which abalone to translocate to the field site vs bring into captivity

6. Moving Black Abalone

If translocating black abalone is decided to be the best decision, discussion is encouraged/required with CDFW, NMFS (Protected Resources Division), National Marine Sanctuaries, California Coastal Commission, Department of Defense and any other agencies whose operations pertain to endangered species and protected resources. Experienced field biologists must be selected to carry out the rescue/relocation operation. Logistical issues must be resolved before the initiation of the rescue operation. Permits and Letters of Authorization to allow for collection, possession and transportation of black abalone must be obtained from NMFS/CDFW. Permits and accommodations at approved facilities will require estimations of the number of black abalone being removed from the site. The translocation team will need to organize accommodations at a holding facility as well as decide upon how to process, tag and record the identity of each individual black abalone being translocated.

The translocation team must identify the most suitable new site to relocate the rescued black abalone, and take into consideration accessibility for transplantation and successive monitoring journeys, protection from poaching, quality of habitat, and the presence of existing black abalone wild or transplanted populations.

During physical outplanting of rescued animals, the black abalone should be placed in rock crevices with “good black abalone habitat qualities” including correct tidal height, protection from predators, and some local wild black abalone present. The cracks and boulders are to be permanently marked by bolts, GPS location recorded, photographed for monitoring identification purposes, and a map of the site drawn with reference points. The local population of black abalone should be counted as well.

7. Mobilizing a team of experts

Once the permits have been acquired and the rescue plan organized, a team of experienced field biologists should carry out the rescue collections during the next daytime negative low tide. The selected participants should have been involved in the initial population survey and habitat assessment, have experience working safely with black abalone, experience transporting black abalone, and experience evaluating black abalone injuries or disease to determine which to collect of those individuals that are accessible at the rescue site. A shellfish pathologist and a representative from the responsible party are recommended.

8. Rescue/Collection of black abalone

A rescue team should survey the affected rocky intertidal habitat to collect data on the number of black abalone, the quality of abalone habitat, the number of abalone accessible for removal, and to estimate the number of inaccessible and impacted abalone who may have been buried or smothered by sediment. Surveying should take place during a daytime negative low tide, preferably with little to low swell action for safety. Black abalone should be collected on the same day or within the same low tide cycle. All injuries to black abalone are to be photographed and recorded, and abalone who are unlikely to survive their injuries are to be sacrificed. Sacrificed abalone should be sent to a lab for genetic analysis and presence of pathogens/infection.

9. Transport and holding of black abalone

Negative daytime low tides (or close to negative tides) and calm sea conditions are required to carry out rescue and translocation operations safely and effectively. It may be necessary to keep the black abalone in a temporary holding facility from one day to several weeks until the appropriate conditions are presented for conclusion of the rescue operation. While being transported, the animals should be wrapped in damp cloths and placed in coolers to maintain a comfortable temperature. The temporary holding facility must be permitted under an ESA Section 10(a)(1)(A) permit and certified sabellid-free. Black abalone health should be continuously monitored, and dead/dying/unhealthy animals should be sent to CDFW Shellfish Health Laboratory for necropsy. Abalone should be tagged and recorded to allow monitoring of survival over time and overall success of the rescue operation.

10. Translocation of black abalone

Translocation operations should be completed as soon as possible after the removal of black abalone from the affected area. All protocols and safety measures should be observed as described above.

11. Follow up

Initial post-transplant monitoring should occur immediately or as soon as possible after the translocation to observe initial movement bursts. Movement of the translocated abalone will diminish with time. Successive monitoring should occur at least once a year to determine rates of movement, tag loss, and survival rates. Ideal frequency of monitoring should be done once per tide cycle (~every 2 weeks) for the

first three months, then once a month for 6 months, and then semi-annually for about a year until the translocated black abalone are no longer identifiable (tag loss, death).

Photo comparison: Aftermath of Mud Creek (2017) and Dolan Fire (2020)

Analysis of sediment movement from the 2020 Dolan Fire Debris Flow - a photo comparison of the same location at two dates over a three-month timespan.



Photos provided by Steve Lonhart - NOAA Monterey Bay National Marine Sanctuary

Big Sur is an especially unique stretch of coastline in central California which is host to designated critical habitat for *Haliotis cracherodii* (Bell & Raimondi 2020). The severe and steeply sloping topography of Big Sur, which faces west towards the Pacific Ocean, combined with an active fault line and seasonal storm activity, makes this a location particularly susceptible to severe landslides and hillside erosion (Hapke & Green 2005, USGS 2005). Occasional wildfires can make the Big Sur coastline more vulnerable to erosion by removing vegetation whose roots hold the soil in place on the slopes (Hapke & Green 2005, USGS 2005).

In Big Sur, the two main ways in which sediments can disastrously affect black abalone habitat in the intertidal zone are through landslides and debris flows (Steve Lonhart pers. corresp.). Photographs (such as those provided above) and drone footage illustrate the changes in sediment and debris levels which were deposited at the ocean-rubble interface after the Mud Creek slide in 2017 and the 2020 Dolan Fire debris flows. To measure sedimentation in rocky intertidal habitats, it is common to measure the spatial extent and amount of sediments accumulated using visual techniques, such as photographs, or videos (Airoldi 2003). Notable landmarks are chosen and highlighted along the beach to act as visual anchors. Photo comparisons over time show that rocks become more exposed as the smaller sediment and sand filling in is slowly washed away. Within even a 3-month timespan post-landslide, there is a remarkable visible difference in the amount of small sediments which have been washed away from the beach, leaving large rocks and cobbles more exposed (Steve Lonhart pers. corresp.)

Mud Creek Landslide (2017)

The footprint of the deposited sediment from the Mud Creek Landslide was observed to be expanding outwards (offshore) and moving up and down-coast in successive months (Steve Lonhart pers. corresp.). The movement of the sediment on and off-shore is motivated by agitating wave action and tidal shifts. The general direction of the prevailing longshore drift current is downcoast (southward), which acts like “a slow conveyor belt” moving sediment down the coastline (Steve Lonhart pers. corresp.). Through this analysis of visual imagery, researchers saw that the boundary of the sediment after these sedimentation events was dynamic, which emphasizes the importance in determining the rate of movement and extent of the burial to determine impacts on black abalone and their habitat (Steve Lonhart pers. corresp.).

“We need to have a better understanding of these sediment dynamics, because this is not going to be the last landslide.” (Steve Lonhart pers. corresp.)

Dolan Fire (2020) Debris Flow

Debris flows are highly destructive landslide-like phenomena that occur on steep hillsides or mountainsides, usually funneling down a canyon or channel, during or following a period of intense rainfall (USGS 2022, Davies 1990, Steve Lonhart pers. corresp.). Recently burned areas are especially susceptible to debris flows, because the loss of soil-securing vegetation and a change in soil characteristics after a fire create a slope especially vulnerable to erosion (USGS 2022, Steve Lonhart pers. corresp.). A debris flow consists of a slurry of water and solids of all sizes forming a heterogeneous fluid with a consistent velocity, essentially a semi-liquid mud slide that is capable of speeds up to 35 mph and of carrying away trees, cars, and massive boulders (USGS 2022, Davies 1990, Steve Lonhart pers. corresp.).

“After the Dolan Fire in 2020, there was an atmospheric river, which brought 17 inches of rain to the Big Sur mountains in a three-day period, depositing this rain directly over the burn scar”, says Steve Lonhart. *“An atmospheric river is essentially... a funnel of a storm system coming over an area with a mega-intense rain.”*

Debris flows are highly erosive (Davies 1990) and are capable of transporting and depositing a significant amount of material at the point where they lose velocity and come to a stop - in Big Sur, this is often at the ocean’s edge (Steve Lonhart pers. corresp.). Black abalone researchers at UCSC and MBNMS monitored the movement of the sediment from its position as a fan after initial deposition from the debris flow to its slow progression down the coast, where it slowly began to encroach upon black abalone habitat. *“We assumed that the sediment would move beyond the boundaries of the debris flow, the question was: how far, and how fast? And what would the consequences be for the abalone populations to the south and the north that [at the end of the rain event] were not (directly) affected [buried] by the debris flow?”* (Steve Lonhart pers. corresp.) Due to the sheer volume of material, this sediment will continue to shift and persist in a way that continues to affect black abalone habitat in the intertidal zone (Steve Lonhart pers. corresp.).

The dramatic topography of Big Sur, and its consequential remoteness, was once a savior for black abalone, acting as a buffer from anthropogenic pressures such as fishing, poaching and coastal development. However, as climate change progresses and weather patterns shift, wildfires and

atmospheric rivers are expected to become more common, and the likelihood of landslides and debris flows with them. This steep stretch of coastline may be an increasingly precipitous safehold for this endangered species, and the protocol for black abalone rescue operations should be refined and at the ready.

Bridget Hoover (2010) Big Sur Fire Study: Winter 2008-2009

The 2010 Big Sur Fire Study report was conducted to determine the effects of recent and historical fires in Big Sur, California on the water quality in affected watersheds which drain into the Monterey Bay National Marine Sanctuary in California. The Basin Complex fire burned from June 21-27, 2008 and the Chalk fire burned from September 27 - October 20, 2008. The study compares data on the relative concentrations of nitrate-N, orthophosphate-P, total suspended solids and transparency before and after these fires. The two hypotheses tested were as follows:

- 1) Burned watersheds have different ambient stream nutrient and transparency levels pre- and post-fire
- 2) Control watersheds will have different ambient stream nutrient and transparency levels pre- and post-fire.

The rainy seasons of 2007-2008 and 2008-2009 received 30.22 inches and 29.98 inches of rain, respectively, which are both ~9.0 inches less than the average rainfall for the region. Data collection/water quality monitoring was conducted three times during the dry season and four times after rain during the study period of September 11, 2008 - May 2, 2009. Six of the data collection sites were located at the base of the watersheds within the burn area, and two sites were located outside of the burn area (one to the north, and one to the south) as control watersheds. The data was organized into three categories based on timing relative to the fires and weather conditions which affect water quality: pre-fire dry, post-fire dry, and post-fire wet.

The results of this study reveal that there are significant differences between nitrate and transparency levels in the dry pre-fire and wet post-fire data groups. There are no significant differences in the dry pre-fire and dry post-fire conditions. The control watersheds (which were not affected by the fires) showed no significant differences in nitrates, orthophosphates or transparency during the study period. The highest nitrate concentrations and largest range of measurements occurred during the period of wet weather post-fire which directly followed the initial dry weather post-fire period. The lowest concentrations of nitrates and smallest range of measures were observed during the dry pre-fire period. Orthophosphate levels were highest and had the greatest range of measurements during the wet-post fire period for most of the watersheds in the study. Total suspended solids (TSS) were highest during wet weather, but there was no data to compare TSS with pre-fire conditions. Transparency levels were lowest in the post-fire wet weather conditions.

“The fact that water quality differences before and after the fires were not detected during dry conditions highlights the importance of hydrologic variability in these watersheds for understanding post-fire sediment and nutrient transport.” - Bridget Hoover (2010) direct quote

Limitations of the study:

Variability in the volume and timing of rainfall and the duration of the wet season throughout the study period affected the character of runoff in the watersheds. The timing of the sampling dates may have missed significant runoff events in which the nutrients and particulates in question were flushed through the watershed. The data may not represent a complete water quality assessment throughout the duration of the study period. The relatively dry meteorological conditions that persisted throughout 2008-2009 were also probably insufficient to mobilize significant sediment movements throughout the study area. It is difficult to draw direct conclusions about fires' effect on water quality when the significant differences in data groups occurred in differing meteorological conditions (wet vs. dry). Recommendations to improve data quality include increased consistency in dates of sampling throughout both wet and dry meteorological conditions and in pre and post fire conditions.

Airoidi (2003) - The Effects of Sedimentation on Rocky Coast Assemblages

“Sediments deeply affect the composition, structure and dynamics of rocky coast assemblages, and increased sediment load as a consequence of anthropogenic activities can be a threat to their diversity and functioning.” - Airoidi (2003) direct quote

Sediment deposition and turbidity are increasing worldwide as a result of expanding anthropogenic activities and global development (Airoidi 2003). Main anthropogenic activities that contribute to an inundation of sediments in coastal marine ecosystems include deforestation, dredging, coastal development and construction of roads, tunnels, bridges and harbors, and mining activities, amongst others (Airoidi 2003). Human activities cause the acceleration of natural rates of soil erosion and result in increased influx of sediments to coastal areas and in nearshore marine environments, which has been recognized as a global threat to marine biodiversity (Airoidi 2003, United Nations Environmental Programme 1995). Concern over sediment accumulation driving habitat degradation has been expressed for a multitude of different habitats, yet rocky coasts are one of these habitats perhaps most sensitive to increased sedimentation levels and could experience dramatic changes in benthic composition as a result of changes in natural sediment dynamics (Airoidi 2003).

In studying sediment movement and its effects, it is important to examine factors such as the sediment characteristics, hydrodynamic conditions (storms and currents), the bathymetry and biological factors of the environment (Airoidi 2003). Primary sources of sediment into coastal aquatic environments can include coastal runoff, discharge by bodies of water (such as rivers and streams), erosion of cliffs and landslides (which result from constant erosion from rain, wind and waves) as well as atmospheric transport and re-disturbance of pelagic detritus (Airoidi 2003). Sediment resuspension and transport are the most frequent source of sediment into new benthic environments (Storlazzi & Field 2000). Storms and currents acting as agitators and drivers of periodic deposition and exhumation are a common feature throughout California (Littler et al. 1983, Stewart 1983). The amount of sediment movement and its influx and settlement in nearshore aquatic environments are highly variable and dependent upon the meteorological conditions (Airoidi 2003).

The composition and volume of sediments that affect a rocky coast benthic environment is highly variable, both spatially and temporally. Sediment may be of varying parent material, grain size and shape, and may include pollutants of human origin, and may be local or transported from a great distance away (Airoldi 2003). Depending on the grain size and composition of the material, sediment deposition may occur quickly, typical of large grain size, or remain suspended in the water column as fine sediments (Airoldi 2003). The often heterogeneous characteristic of sediments results in varying effects on rocky coast habitat and the organisms which inhabit them (Airoldi 2003).

According to Airoldi (2003) the three main major mechanisms by which sediments may affect rocky coast assemblages include:

- 1) Burial and/or smothering, resulting in reduced light availability, reduced oxygen and nutrients availability, and may cause the accumulation of hydrogen sulfide and organic waste products which, once built up, can be detrimental to all biological organisms in the area
- 2) Scour and abrasion, which can cause extreme stress and damage to biological organisms
- 3) Altered composition of the physical benthic marine environment, including replacing hard substrata with soft/unstable particles and reduced habitat suitability for benthic organisms.

These three main mechanisms are most likely constantly working in conjunction with one another in benthic marine environments and function as a natural source of stress and disturbance (Airoldi 2003).

Seasonal burial and exhumation

The movement of unconsolidated seafloor sediments along the coast of California are governed by such factors as the seasonality of storms, wave height, energy, current, and direction. These natural forces create cycles of sediment deposition and exhumation along a differentially affected “mosaic” of the seafloor to which coastal benthic communities are highly adapted and reactive (Storlazzi et al. 2013, Figurski et al. 2016). Sediment movement also creates conditions of turbidity and scour which can be highly disturbing to the seafloor ecology (Figurski et al. 2016). Sediment deposition and accumulation will differ depending on an area’s exposure to wave energy, sediment composition, and bathymetry (Storlazzi et al. 2013, Figurski et al. 2016). Areas of the seafloor in high relief are typically less susceptible to sediment accumulation than low relief areas (Figurski et al. 2016). Along the coast of California, spring and summer are typically periods of low wave energy and short-period swells, whereas the winter season exhibits more deep-reaching and energetic storm activity, both of which have marked effects upon the movement of seafloor sediment (Storlazzi et al. 2013).

“Repeated surveys of the sea floor in northern Monterey Bay, California (Storlazzi et al. 2011) showed that up to 30% of the sea floor was buried or exhumed over the winter of 2005.”

- (Storlazzi et al. 2013) direct quote

Biological factors are observed to control or affect the deposition or distribution of sediments along nearshore marine environments (Airoldi 2003). Eelgrass beds can bind and stabilize sediments, thereby creating a more consistent sediment accumulation in the area regardless of variability in sediment load (Stewart 1983). Kelp forests have been known to accelerate and stabilize sediment deposition, and in other situations, prevent accumulation of sediments (Moore 1972, Kennely 1989).

Sediment dynamics play a noteworthy role in determining the community structure of near-shore benthic ecosystems by facilitating continuous disturbance and ecological succession. The Intermediate Disturbance Hypothesis (IDH), first proposed by Joseph Connell in 1978, explains how overall species diversity can be promoted through the reduction of competitive dominant species. Moderately infrequent weak or medium severity disturbances will upset the ecological position of competitively dominant species (such as mussels) and make room for new species, thereby allowing for a higher diversity of species within a community (Connell 1978). These new species are typically early colonizers, fast growers, and disturbance tolerant. The IDH is an important concept in considering disturbances as essential to the health and biodiversity of ecosystems, and in studying community responses to seasonal disturbances as they occur in dynamic environments (Connell 1978).

In a comparison between stable (where exposed bedrock is present throughout the year) and dynamic (exhibiting seasonal sediment changes) rocky reef plots in Monterey Bay, California, it was determined that seasonal sediment dynamics have a detrimental impact on the overall species diversity of benthic communities present on the selected dynamic plots (Figurski et al. 2016, Storlazzi et al. 2013). *“At the study sites, local species diversity and richness of benthic communities was up to 50% lower in disturbed (i.e. dynamic) versus stable plots (Storlazzi et al. 2013), suggesting that the effects of sediment scour and direct burial are severe for benthic species associated with the rocky reef” (Figurski et al. 2016 direct quote)*. In the study, the stable plots were observed to host a greater number and diversity of mobile and sedentary species. Mobile species such as fish are observed to simply relocate to a cleaner or more hospitable environment in the event of heavy sediment deposition (Storlazzi et al. 2013, Figurski et al. 2016). Sessile and sedentary species are not as capable of moving to avoid a heavy sediment load, and therefore are more likely to be present in a constantly stable environment (Storlazzi et al. 2013, Figurski et al. 2016).

When observed from a broader viewpoint, a “mosaic” of dynamic and stable plots can effectively increase species diversity in the regional community (Figurski et al. 2016). Certain species depend upon constant disturbance to secure a foothold in the competitive complexities of continual growth and movement. It is important to recognize also that much of the near-shore marine environment is not composed of either completely “stable” or completely “dynamic” plots, and that a variable level of sediment dynamicity must be expected in most areas, and that the diversity of benthic communities will be adapted to the relative dynamicity of their environment (Storlazzi et al. 2013, Figurski et al. 2016).

Although the specific consequences of sediment dynamics for *Haliotis spp.* are not mentioned directly in Figurski or Storlazzi’s work, it can be conservatively assumed that more stable benthic environments will be hospitable to greater population sizes and recruitment. Abalone, a relatively sedentary and slow-growing species, are less likely to survive or settle in an area where sediment dynamics are rapidly and continuously shifting (Phillips & Shima 2006, Onitsuka et al. 2008, Chew et al. 2013). *“The negative effects of burial, increased turbidity, and scour associated with seasonal sediment movement can have community-level consequences by influencing all life history stages of benthic species, from settlement to reproduction.” (Figurski et al 2016. direct quote)* If larvae do survive, settle, and metamorphose, burial beneath sediment remains a constant threat to survival for many benthic-dwelling reef species (Figurski et al 2016).

Climate change has the potential to radically alter these temporally consistent seasonal cycles of sediment shift in near-coastal ecosystems. Increasing sea surface temperatures are observed to increase the frequency and severity of storm events which cause coastal erosion and increase sediment load in the water (Storlazzi et al. 2013). The range of benthic ecosystems affected by sediment dynamics could extend further from the shoreline, and increased severity of sediment load/turbidity could potentially reduce the resiliency of ecosystems to seasonal sediment dynamics. The ability of species to relocate/adapt can easily be diminished by a deviation from accustomed and reliable sedimentation dynamics.

Altered environment, behavior & survival

“The recruitment failure of black abalone may be attributable to a combination of the above explanations: an inadequate larval supply, shifts in community structure unsuitable for early settlement and survival, and the possible persistence of withering syndrome.” - Miner et al. 2006 direct quote

Further studies that investigate the full effects of these stressors on black abalone are encouraged.

Disclaimer:

It is important to note that many of the studies referenced in this literature review were not conducted on the main abalone species in question: Black abalone, *Haliotis cracherodii*. Many studies have been conducted on a variety of abalone species including *H. rufescens*, *H. iris*, *H. diversicolor*, *H. laevigata*, *H. scalaris* and *H. rubra* which inhabit the intertidal and subtidal zones in a variety of ranges across the planet. It is inadvisable to assume direct correlation between the results of experiments conducted upon these various other abalone species and the similarities in reactions of *H. cracherodii*. The selected information is provided so that the reader may make informed decisions and conclusions regarding black abalone habitat restoration and rescue operations as they arise.

Phillips & Shima (2006) - Effects of sediments on larval survival of New Zealand urchins *Evechinus chloroticus* and abalone *Haliotis iris*

This study focuses on identifying the effects of varying concentrations of suspended sediment on the development, settlement, and survival of larval *Haliotis iris*. In the lab, abalone larvae were exposed to various concentrations of sediment collected from the mouth of a local river emptying into Wellington Harbor, New Zealand. The sediment concentrations were intended to mimic the effects of terrestrially derived runoff following a heavy rain event. Larval survival and mortality rates were collected for Ambient, 0.5x Ambient, 1x Ambient and 2x Ambient sediment concentrations, as well as exposure to 2x Ambient sediment concentrations “Early” in development (1-3 days postfertilization) and “Late” in development (3-6 days).

High sediment concentration was observed to alter larval development and physical structure, resulting in significantly longer protoconchs in abalone larvae exposed to high concentration sediment (acute exposure). The presence of any amount of sediment seemed to favor the survival of larvae who were generally larger in some dimension than their unsuccessful counterparts and may have implications for the surviving larvae population’s ability to feed in turbid environments.

The timing of sediment exposure is also significant to larval mortality rates. “*H. iris* larvae exposed to sediments early in their development suffered 13% greater losses than *H. iris* larvae exposed later in their development.” (Phillips & Shima 2006 direct quote). Larvae who were raised in ambient sediment concentrations displayed high mortality rates when later exposed to sediment at any concentration. The study concluded that short-term exposure to acute sediment concentrations generally resulted in higher larval mortality rates, and *H. iris* larvae did not respond well to sediment exposure at any concentration or in any stage of development (Phillips & Shima 2006). High mortality rates for larval abalone persisted even after the removal of sediments from the water, although certain larval stages exhibited delayed responses to acute sediment exposure (Phillips & Shima 2006).

At all sediment concentrations, larval *Haliotis iris* displayed higher per capita mortality rates and unusual/disformed larval appendage development which has implications amongst even the survivors for reduced survival rates in later stages of development. The conclusions of this study reinforce that the negative effects of sediment exposure increase with concentration and duration, with even temporary exposure to a turbidity plume of high sediment concentration inducing larval mortality and lasting effects on developing population dynamics (Phillips & Shima 2006).

Onitsuka et al. (2008) - Effects of sediments on larval settlement of abalone *Haliotis diversicolor*

In studying the effects of sediment upon recruitment success in abalone, Onitsuka et al. acknowledged that “*recruitment success is influenced by both settlement success and early post-settlement mortality.*” Sediments both suspended and settled, and how these sediments affect both larval development and favorable habitat conditions, must be considered in studying factors affecting larval settlement and recruitment success. For example, sediment accumulation may interfere with the growth or availability of crustose coralline algae (CCA), which is observed to induce larval settlement and metamorphosis once larvae are fertilized in the water column (Onitsuka et al. 2008). Sediments can also effectively “trap” larvae and prevent their metamorphosis (Onitsuka et al. 2008). Larval metamorphosis is observed to be significantly higher in the absence of sediments, and rates of larval settlement and metamorphosis decline in correlation with increases in sediment concentration, both suspended in the water column and as sediment accumulated on the substrata (Onitsuka et al 2008).

Chew et al. (2013) - Low level sedimentation modifies behavior in juvenile *Haliotis iris* and may affect their vulnerability to predation

An additional study conducted by Chew et al. focused on potential behavioral shifts in juvenile individuals in reaction to anthropogenically-sourced sedimentation events. The study was motivated by a proposed dredge spoil disposal of >7 million cubic meters from the Otago Harbor in Dunedin, New Zealand, which would undoubtedly impact nearby benthic communities, perhaps resulting in irreversible damage to populations of *H. iris*, a species of interest, in the area. Anthropogenic activities that directly increase sediment load to the water column often include the dredging of bays and harbors and coastal development (Airoldi 2003). Sediments from anthropogenic sources (such as dredging) are more likely to be large-scale, widespread and persistent (Airoldi 2003), and are more likely to limit or prevent abalone attachment to the substrate and ultimately result in increased stress and predation mortality among

Haliotis spp. (Shepherd & Turner 1985, Chew et al. 2013). It is essential to study the effects of these events on larval abalone and recruitment success to organize and prepare effective prevention, remediation, or rescue operations to assist *Haliotis spp.* in the future.

The study (Chew et al. 2013) tested the effects of sedimentation events on 1) the behavior (esp. attachment failure and righting response ability) and mortality rates of juvenile *H. iris* and 2) the photosynthetic vitality of coralline crustose algae (CCA), which provides important nursery habitats for abalone (Shepherd & Cannon 1988). Past studies have confirmed that the presence of sediments suspended in the water column can significantly increase the mortality rates of larval *H. iris* and sediments deposited in a layer over the substrate prevent larval settlement and metamorphosis (Phillips & Shima 2006, Onitsuka et al. 2013).

The study observed that where moderate sediment load in the water column may not be directly fatal to juvenile or adult abalone, sediment can alter abalone behavior in a manner that increases their vulnerability or susceptibility to predation (Chew et al. 2013). Sediment was determined to significantly inhibit abalone's righting response, and abalone subjected to high and low concentrations of sediment deposition were twice as likely to be on the side (vertical positioning) of the tank than those in control (no sediment) tanks (Chew et al. 2013). Preferable habitat for *Haliotis spp.* consists of bare rock, a cover of coralline crustose algae, and rocky gaps between boulders which together ideally provide abalone a suitable surface to adhere to, safety from predators, and food access (Steneck 1982, Steneck 1997, Shepherd & Turner 1985). *H. iris* who relocate from “refugia” (safe, protected areas between cobbles) to exposed locations on a vertical surface are significantly more vulnerable to predation and dislodgement (Chew et al. 2013). The study concludes that sediment exposure could cause significant indirect mortality of *H. iris* from secondary causes such as increased exposure to predation and inability to reattach to the substrate after dislodgement (Chew et al. 2013). The indirect effects of sedimentation on *H. iris* habitat could have serious implications for the long-term sustainability of abalone populations in the region.

Coralline Crustose Algae and *Haliotis spp.*

Coralline crustose algae (Rhodophyta, Corallinaceae) are shown in many studies to be an important biotic characteristic that is associated with high densities and healthy populations of *Haliotis spp.* (Strain and Johnson 2010, Shepherd & Turner 1985, Naylor et al. 2006, Chew et al. 2013). Coralline crustose algae (CCA) produces chemicals which induce larval settlement and metamorphosis of many abalone species, including the New Zealand abalone *Haliotis iris* (Naylor et al. 2006), *H. rufescens* and *H. fulgens* (Morse & Morse 1984) and *H. laevigata* and *H. scalaris* (Shepherd & Turner 1985). The available cover of CCA is therefore considered a requirement for encouraging heightened recruitment rates in a localized abalone population (Naylor et al. 2006, Chew et al. 2013). CCA provides a critical food source for juvenile abalone (Shepherd & Cannon 1988) and also lends a camouflaging color to their shells, allowing them a further mechanism against predation (Shepherd & Turner 1985). In certain species of abalone, juveniles smaller than 5mm in diameter are restricted to a substrate composed of coralline crustose algae (Shepherd & Turner 1985).

There is continued discourse and deliberation over the effects of sediment on encrusting coralline algae. Some studies propose that crustose coralline algae are negatively affected by sediments and that

increased sediment load reduces habitat suitability for *Haliotis spp.* by reducing cover of coralline crustose algae (Shepherd & Turner 1985, Steneck 1997). Coralline crustose algae cover was, in some studies, observed to have a negative correlation with increased sediment deposition, which can be measured through bleaching of CCA, amount of growth, or photosynthetic vitality (Steneck 1997, Chew et al 2013). Certain species of CCA are vulnerable to siltation because the deposition of fine sediments can prevent CCA recruitment and restrict gaseous flow and light availability (Connell 2005). However, other studies provide evidence that the presence of sediment does not have a strong negative effect on cover of certain crustose algae species (Chew et al. 2013), or that encrusting coralline algae are abundant and may dominate in an environment affected by high levels of sedimentation. (Littler 1973, Airoidi et al. 1995). Certain species of coralline crusts are even observed to be benefitted by sediment scour, which reduces spatially competitive species of algae, but are overgrown by these species in situations promoting sediment accretion (Kendrick 1991).

The best conclusion is to admit that both scenarios are possible - that some types of crustose coralline algae are positively affected by sediments, and others are affected negatively. Crustose coralline algae are highly diversified and should not be considered all dependent upon similar environmental conditions and community characteristics to thrive (Steneck 1987). It is important to note that some species of CCA are more tolerant to sediment deposition than others, and if a certain species of CCA that demonstrates high recruitment survival in larval abalone also demonstrates low sediment tolerance, it could have a strong negative effect on *Haliotis spp.* recruitment and survival (Chew et al. 2013).

Aalto et al. 2020- Abalone populations are most sensitive to environmental stress effects on adult individuals

Anthropogenic impacts on the environment, especially considered in combination, can increase the vulnerability of an abalone population by reducing their resilience to additional stress or disturbances (Aalto et al. 2020). Changing environmental conditions can include increases in temperature, the spread of diseases beyond their natural range, anoxic and hypoxic conditions, ocean acidification, pollution from terrestrial runoff, and sedimentation events from dredging and coastal development (Aalto et al. 2020, Chew et al. 2013, Airoidi 2003). Long-term population dynamics of abalone species are dependent upon the reaction of reproducing individuals to negative stressors. While mass-mortality events associated with extreme weather (hurricanes, warm-water spells) are expected to increase in the coming years (IPCC 2022), it is especially important to study the quantitative effects of combined stressors on abalone populations to determine the extent and urgency of conservation and population supplementation efforts.

In a study conducted by Aalto et al (2020), computer models were used to determine the effects of gradually increasing ocean acidification (OA) on the resiliency of a “continuous size-structured” simulated abalone fishery (*Haliotis spp.*). The parameters chosen test different aspects of abalone life history: recruitment (larval production, allee sensitivity), survival (juvenile, subadult and adult) and growth (growth rate, maximum size, and size at maturity).

The study outlined its three main goals as such:

- 1) *Focus on how declines in each parameter would affect a theoretical biomass and catch number under a scenario of gradual ocean acidification,*

- 2) *Simulate a sudden mass mortality event to explore whether the long-term effects of a stressor such as OA could affect short-term resilience to catastrophe by delaying or preventing population and fishery recovery,*
- 3) *Combine small simultaneous changes in recruitment, growth, and survival parameters to determine if negative interactive effects would exceed the expected additive outcome*
(Aalto et al. 2020 direct quote).

Abalone were selected as the subject of these OA models because they are considered of particular importance as a calcifying organism and a species of conservation importance. The main goal of the study is to identify how multiple stressors may affect fertilization success and survival of individuals across multiple life stages, thus affecting the long-term population dynamics of abalone in the simulated fishery.

The study concluded that the most significant impacts to population dynamics were those which impacted the growth and survival of “large, fecund adults.” While there are many studies identifying the stress tolerance of larval and juvenile abalone, Aalto et al. (2020) determines that adults who have reached sexual maturity and the reproductivity stage are in fact the most important players in terms of population growth and sustaining a healthy population size. *“Because fecundity scales exponentially with size, decreasing the growth rate, maximum size, or adult survival has a disproportionate impact on overall larval production across the entire lifespan of an individual”* (Aalto et al. 2020 direct quote).

Self-sustaining populations, therefore, must consist of a healthy number of large, reproducing adults who are in close proximity to one another to ensure fertilization, which is supported by a number of other studies. Abalone are especially susceptible to gradual population declines when grouped in low densities, even without the added pressure of a disturbance or other stressful environmental factor.

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