PUGET SOUND RESTORATION FUND

RECOVERY PLAN FOR PINTO ABALONE (*HALIOTIS KAMTSCHATKANA*) IN WASHINGTON STATE

(USING A COLLABORATIVE MANAGEMENT APPROACH)

MARCH 2014

Executive Summary

Current Status

Pinto, or northern, abalone populations in Washington State are severely depressed and continue to decline. Effective recovery of pinto abalone will require not only a halt of population decline but a reversal of this declining trend. Given the low population densities, it seems unlikely that such a reversal will be possible without an active supplementation program that relies on hatchery stocks, in addition to other active recovery strategies.

Populations of pinto abalone in Washington State are presently well below the presumed minimum threshold density range of 0.15 to 0.30 individuals m^{-2} that allows successful fertilization. Furthermore, based on an increasing mean shell length in surveyed populations, and few, if any, observations of small abalone (recruits), it is apparent that populations are aging without replacement by younger individuals.

Until populations are considered to be above a minimum density for natural reproduction and size structure observations indicates strong recruitment, pinto abalone in Washington State are at risk of extirpation.

Formal risk status designations of pinto abalone in Washington State are Washington State Candidate Species, Washington Species of Greatest Conservation Need, and Federal Species of Concern. In 2013 two petitions were submitted to list pinto abalone under the Federal Endangered Species Act as either a Threatened or Endangered Species.

Recovery Goal

The goals of abalone recovery efforts in Washington State are to reverse the decline of pinto abalone stocks and to attain self-sustaining populations throughout regions of historic abundance in the State.

Recovery Strategies

The strategies needed to increase the size and density of pinto abalone populations to a self-sustaining level (i.e., recovery) will require a multi-faceted approach of education, restoration and management.

Continuous index site monitoring will be essential to evaluate the success or failure of recovery efforts. Efficacy of recovery will be measured in the same way that declines have been quantified among surveyed populations: (1) changes in mean shell lengths (size structure); (2) nearest neighbor assessments and; (3) densities (numbers of animals per area).

Maintenance of fishery closures and diligent enforcement will be necessary to prevent the further decline of abalone populations while we develop new strategies to facilitate population recovery.

Education and public outreach will help reduce the risk of accidental poaching of abalone by those individuals who may be unaware of the status of abalone populations in the Pacific Northwest. Furthermore, by increasing awareness among the public and by involving them in restoration efforts, we aim to develop a greater sense of stewardship and conservation of the species and hope to reduce the demand for illegally harvested abalone.

Creation of artificial aggregations of adults may help bolster the reproductive potential of spatially isolated adults that currently have a low chance of successful reproduction. Abalone are broadcast spawners that rely on the opportunistic encounter of their gametes (eggs and sperm) in the water. Gametes must be at sufficient concentrations to allow fertilization of eggs by sperm and thus for recruitment to be successful.

Rotation of hatchery broodstock into wild spawning aggregations will enable us to use wild abalone to optimize genetic diversity in remote upland production and then return these same individuals to marine waters where they may further contribute to wild production. By returning healthy adults to the wild proximate to other mature abalone, increased densities may help to promote successful spawning in aggregations.

Improvement of husbandry and hatchery techniques will be necessary to scale-up conservation aquaculture operations. Barriers still exist for the reliable production of hatchery pinto abalone to outplant size. These barriers primarily include gonad conditioning, spawning induction, and early post-settlement growth and survival. To maximize genetic diversity and the number of distinct families produced within the hatchery that are subsequently outplanted to restoration sites, hatchery and nursery techniques need improvement.

Expanded studies on the role of extrinsic barriers to recruitment success will enable us to better understand the processes that may be affecting abalone survival and development in the wild. While one of our working hypotheses is that low reproductive success due to low population density is currently the greatest impediment to successful recruitment, a better understanding of extrinsic barriers (e.g., environmental conditions) to recruitment success will guide the processes by which other restoration strategies are implemented.

Large-scale outplanting represents one of the most substantial efforts for abalone recovery. Pilot studies have informed our team with respect to optimization of outplant densities, abalone sizes and re-introduction techniques. Pinto abalone have been outplanted at multiple locations in the San Juan Archipelago to supplement extant populations with an objective of maximizing genetic diversity. A second objective is to raise population densities above the minimum threshold density range associated with population collapse (0.15 to 0.30 abalone m^{-2}). Recent trials to outplant larvae at the settlement stage may help, both to reduce hatchery selection and to optimize limited hatchery resources by reducing nursery time. Survival of outplanted larvae will be assessed in 2014.

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LIST OF ACRONYMS AND ABBREVIATIONS

BC – British Columbia
ESA - Endangered Species Act
IUCN – International Convention for the Conservation of Nature and Natural Resources
MLLW – Mean Lower Low Water
NMFS – National Marine Fisheries Service
NOAA – National Oceanic and Atmospheric Administration
PSRF – Puget Sound Restoration Fund
SARA - Species at Risk Act (Canada)
SJA - San Juan Archipelago
SPMC – Shannon Point Marine Center, Western Washington University
UW – University of Washington
WDFW - Washington Department of Fish and Wildlife

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Jamestown S'Klallam Tribe

Washington Department of Natural Resources

LEGAL FRAMEWORK

The Washington Department of Fish and Wildlife operates as the state's principal agency for species protection and conservation, under a legislative mandate defined in Title 77 of the Revised Code of Washington (RCW). That legislative mandate directs the department to preserve, protect, perpetuate and manage fish, wildlife and shellfish. As this mandate applies to pinto abalone, it is the role of WDFW to maintain and enforce closures for the harvest of this resource and work to improve population status until such time that its biologists deem the populations to be sufficient to provide a sustainable recreational and/or commercial opportunity. Fish and wildlife resources are equally important to the Tribes, who have affirmed natural resource rights in federal court decisions.

INTRODUCTION

Species Information & Nomenclature

Taxonomy: Kingdom: Animalia
Phylum: Mollusca
Class: Gastropoda
Subclass: Prosobranchia
Order: Vetigastropoda (Archaeogastropoda)
Superfamily: Pleurotomariacea
Family: Haliotidae (abalone)
Genus: *Haliotis*
Species: *kamtschatkana*

Common name:
In the United States, the most common name used is 'pinto abalone' (which describes the yellow and brown mottling of the epipodium), and in British Columbia, the common name generally used is 'northern abalone' (to describe the northernmost species of haliotid). For the sake of consistency with existing Washington State documentation, we use the common name 'pinto' throughout this document, but acknowledge that 'northern' is equally acceptable.

Status:
Populations have been declining, even after closure of the recreational fishery in 1994, likely because population densities are too low for successful reproduction.

> *U.S. Federal Status*: Species of Concern.
> ESA petitions received by NOAA in 2013 to change status to "Threatened" or "Endangered".
> *Washington State Status*: State Candidate Species and Species of Greatest Conservation Need.
> *Other relevant designations*: Canadian Endangered Species (under SARA); IUCN red list 'endangered' species.

Description

Pinto abalone are medium sized abalone (marine snails), generally about 110 mm in shell length as adults, but they may approach 160 mm. Their epipodia are mottled brown and yellow and the exterior of their shells can also have a mottled appearance, giving them the common name of "pinto." This species generally has a row of 3-6 open, raised respiratory pores with a groove running in between the row of pores and the margin of the shell. The head and foot are surrounded by epipodial tentacles that sense their surroundings. The herbivorous pinto abalone can move to graze on benthic diatoms, capture and consume drift macroalgae, and avoid predation. Like other abalone species, pinto abalone are dioecious broadcast spawners, meaning that individuals are either male or female and eggs and sperm are released into the water for potential fertilization (Campbell *et al*. 2000).

Populations and Distribution

Pinto abalone are distributed from Point Conception, CA to southeast Alaska (Fig. 1), making them the northernmost Haliotid species. McLean (1966) reported a southern range to Baja California, Mexico but specimens are not available to confirm this report. They are generally found on hard, rocky substrates in exposed coastal areas, including the Puget Sound, Strait of Juan de Fuca and the San Juan Archipelago.

Figure 1. General historic distribution of pinto abalone (*Haliotis kamtschatkana*) and current harvest status summary by respective jurisdictions.

Populations in Washington State have never been subject to a commercial fishery but they were harvested recreationally for several decades, until the fishery was closed in 1994. Populations in Washington have been surveyed using various methods since 1979 and at well-defined index sites (Fig. 2) in the SJA since 1992. Abundance at index sites in the SJA has declined 92% between 1992 and 2013 (Rothaus *et al*. 2008, WDFW unpublished data) (Table 1).

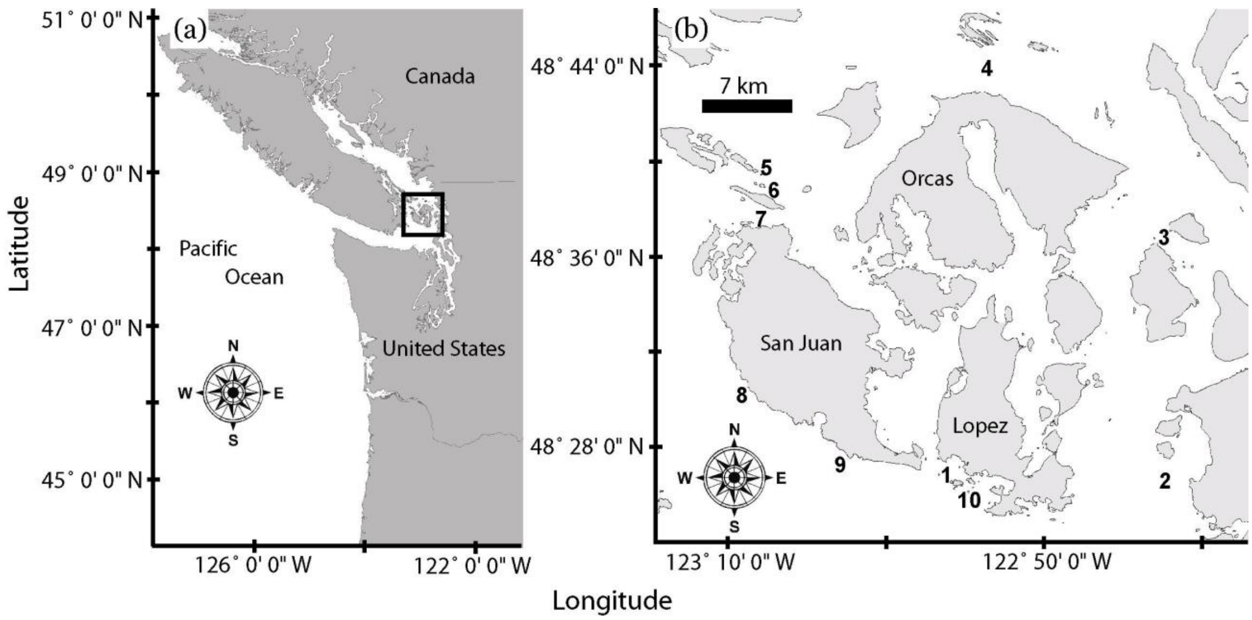

Figure 2. Pacific Northwest Region map (left) and expanded inset box with locations of pinto abalone index stations in the San Juan Archipelago (SJA), Washington (right), (from Rothaus, *et al*. 2008).

TABLE 1.
Summary of pinto abalone shell length (SL) measurements from 10 index sites in the San Juan Archipelago.

Year	n	Mean SL	C.I. (α=0.05)	Minimum SL	Maximum SL
1992	340	105.3	1.73	42	142
1994	281	107.8	2.07	53	145
1996	268	107.5	2.18	41	145
2003	136	114.8	2.70	46	146
2004/2005	103	113.7	2.83	56	141
2006	104	115.4	2.42	80	139
2009	60	115.5	4.37	71	147
2013	56	118.4	4.97	55	152

Pinto abalone populations in California and Oregon lack formal surveys/stock assessments and there are neither commercial nor recreational fisheries for pinto abalone in either state. Populations are in decline in British Columbia, Canada, where fishery closures and restoration efforts have been on-going for more than a decade (Lessard and Egli 2011). A recreational fishery still exists in Alaska, but concerns about population levels resulted in a commercial fishery closure in this region as well.

Exploitation history

In Washington, no commercial fishery for pinto abalone existed. Exploitation of pinto abalone via the legal recreational fishery, though authorized in 1959, was never well-documented. Thus estimates of the number of abalone extracted from Washington State during this period are poor.

Based on surveys and interviews with boat captains, Bargmann (1984) estimated that approximately 38,200 abalone were harvested per year in Washington, predominantly from the SJA, during the early 1980s. Estimates in the early 1990s were expanded to nearly 41,000 abalone per year (Gesselbracht 1991). Palsson *et al.* (1991) collected information from dive charter boats in Washington and estimate a peak pinto abalone catch of 2.28 abalone per dive in 1981 and a mean catch of 1.57 abalone per dive from 1979 to 1985. Recreational harvest restrictions were imposed in the early 1990s and the recreational fishery was closed in 1994 as a result of concerns regarding population declines.

The nearby British Columbia fishery reported commercial harvests in the late 1970s as high as 400 metric tons of abalone per year. Scarcely a decade after this peak in the fishery, the Canadian government closed both the commercial and recreational harvests of abalone in 1990. Fisheries for pinto abalone in both the U.S. and Canada have remained closed through 2014.

Ecology of Pinto Abalone

Habitat and biological needs

Pinto abalone are typically found on rocky substrate, between 3 and 20 meters of water depth in the Pacific Northwest (Sloan and Breen 1988). Their preferred habitat in the SJA and the Strait of Juan de Fuca is exposed rock, often covered (at least partially) with crustose coralline algae (CCA), which may be used as a settlement cue for abalone larvae (Roberts 2003).

Adult pinto abalone feed primarily on drift macroalgae, such as *Nereocystis luetkeana* (bull kelp), and juveniles feed predominantly on microalgae and diatoms.

Pinto abalone are broadcast spawners with a relatively short period of gamete viability, which necessitates aggregations of adults in order for reproduction to be successful. After eggs are successfully fertilized, embryos rapidly become swimming trochophores, which metamorphose into veliger larvae at approximately 24-48 hours post-fertilization. The swimming veligers settle onto suitable substrate, probably cued by CCA (Morse *et al*. 1984), after approximately 10-14 days as plankton (Sloan and Breen 1988; Pearce *et al*. 2003). Newly settled juvenile abalone require crevices for added protection from predators and remain cryptic in the habitat until mature. Upon maturation at approximately 50 mm in shell length, abalone become emergent and can be more easily found in their habitat. Many pinto abalone are semi-exposed or fully exposed on open rocky habitat by 90 mm shell length.

Ecological Role

Abalone play a critical role in the rocky subtidal as a primary consumer by grazing, digesting, and excreting micro- and macro- algae. Abalone alter their environment by grazing preferentially on certain species, and as primary consumers they provide a critical ecosystem function by increasing species diversity by clearing habitat space for settlement of new recruits, improving nutrient cycling, improving habitat resilience to perturbations, and providing food to prey species.

Vulnerabilities

Pinto abalone are particularly vulnerable to fishing predation because 1) they are sedentary and contagiously distributed, giving rise to serial depletion of aggregations by fishers; 2) they typically occur in shallow subtidal areas and may have no deep water refuge from harvesters; 3) they are prized by fishers and consumers; 4) their recruitment may be dependent on localized larval production and settlement due to their 10-14 day planktonic larval stage; 5) the cryptic nature of juveniles combined with the longevity and slow growth of adults may mask recruitment failure over several years, complicating fishery management; and 6) long lived, broadcast spawning invertebrates, like abalone, may exhibit high interannual recruitment variability (Rothaus *et al*. 2008).

Description of Threats to Abalone Populations

Recruitment failure

Perhaps the greatest threat to the perpetuation of abalone is the strong evidence of recruitment failure among surveyed populations. Data from the SJA support this observation because the mean shell length is increasing and observations of juveniles less than 50 mm in length are almost non-existent. This suggests that populations are aging without replacement by younger (smaller) individuals (Rothaus *et al*. 2008, Bouma *et al*. 2012). Several possible explanations for such recruitment failure may exist.

Depensatory (Allee) effect

Low population densities can negatively affect population growth rates via recruitment failure. This depensatory mechanism, or Allee effect (Allee 1949), may explain the perpetuation of population declines despite more than a decade of fishery closures. Zhang *et al*. (2007) did not observe a depensatory effect in Beverton-Holt stock-recruit models at low spawning stock biomass for *H. kamtschatkana*, though several studies did observe a weak depensation with Ricker models for *H. laevigata* (Shepherd *et al*. 2001; Shepherd and Partington 1995). In

Washington, early population declines were likely the result of over-exploitation and some fraction of this decline was (and perhaps still is) the result of poaching. Taken together, over-exploitation and declining density in spite of fishery closure suggest a depensatory recruitment failure, as indicated by an increase in the mean length of abalone (Table 1).

While emergent abalone < 90 mm comprised 16% of individuals in the 1990s, less than 6% of the population was in this size class from 2003 to 2006 (Rothaus *et al*. 2008). At five of the ten index sites surveyed in 2003 no emergent abalone were observed and less than ten emergent abalone were observed on the remaining 5 index sites. By 2013 five of the ten index sites were fully extirpated and the remaining 5 sites had densities below 0.1 abalone m^{-2}. In addition, the mean shell length of abalone between 1992 and 2013 increased 13.1 mm, suggesting that abalone in the SJA are continuing to age without replacement. Davis *et al*. (1996) observed a similar trend in length frequencies of endangered white abalone (Federal Register 66(103) 50 CFR Part 224, May 29, 2001), and suggested that the observed recruitment failure was a key factor in the demise of white abalone populations.

As broadcast spawners, abalone require a threshold density to achieve reproductive success. If populations fall below this threshold density, they can experience recruitment failure or a mating related Allee effect. Allee thresholds specific for pinto abalone are unknown. In general, broadcast spawning sedentary invertebrates (such as abalone) must be aggregated above a minimum density range of 0.15 to 0.30 individuals m^{-2} for successful fertilization and prevention of stock collapse (Babcock and Keesing 1999). In abalone, fertilization inefficiencies may be exacerbated by a tendency toward episodic spawns (Tegner *et al*. 1989, McShane 1992, Shepherd and Daume 1996). Thus, although early declines may have been the result of fishing, continued declines suggest recruitment failure as a major cause.

Adult condition

Adult pinto abalone may be experiencing intrinsic and extrinsic conditions that affect reproductive success. Factors such as reproductive senescence and changing ocean chemistry (including ocean acidification) may be factors contributing to reduced spawning activity, reduced gamete production and poor gamete condition (Friedman *et al*. unpublished data).

Larval dispersal

Abalone larvae have a planktonic phase that may last as long as two weeks so it is feasible that the recruitment failure observed in the SJA may be the result of changes to source populations such that larvae are no longer being imported to the SJA. For example, a shift in the physical oceanography (water currents) of the region (perhaps accompanying recent changes in SJA temperature and salinity [Masson and Cummings 2004]) may have altered the import or the retention of abalone larvae. The densities of distant source populations may have declined, contributing to depensation.

Settlement habitat has changed/diminished

The association between abalone larvae and crustose coralline algae (CCA) as a settlement surface has been well-documented (Morse & Morse 1984). Settlement of abalone larvae on CCA has been correlated with biological (Miner *et al*. 2006) and chemical cues (Li *et al*. 2006; Morse 1992; Morse *et al*. 1979). Thus changes in the marine environment that alter either the availability of CCA surfaces or the cues associated with these surfaces may impede the settlement of abalone larvae. Further, a lower density of abalone results in less localized "conditioning" or cropping of substrate surfaces, thereby reducing the amount of settlement habitat. The result may be a negative feedback mechanism contributing to depensatory effects.

Recruitment mortality

It is currently not feasible to monitor wild abalone reproduction and settlement. Reproduction may be sufficient, yet additional factors may be causing increased mortality of newly settled juvenile abalone, precluding recruitment. Such factors as food limitation, environmental change, disease or increased early stage predation could all be relevant but are as yet undiscovered.

Mortality

Abalone undergo several distinct life stages during which time they are differentially vulnerable to a suite of biotic and abiotic factors. Several documents review abalone mortality (e.g., National Marine Fisheries Service 2009; Shepherd and Breen 1992) and identify such factors as predation, poaching, variation in food supply, physical disturbance, pollution, disease, environmental change and habitat alteration.

Predation

Predators may exacerbate population declines and may complicate restoration strategies. There are many possible predators of larval abalone and recently settled juveniles (including "polychaetes, nematodes, polyclad flatworms, and anemones"; National Marine Fisheries Service 2009; Shepherd and Breen 1992). Griffiths and Gosselin (2008) conducted controlled experiments and observed predation of juvenile abalone by as many as 14 naturally encountered predators (including fish, crustaceans and echinoderms). Meanwhile adult abalone are vulnerable to several of the same predators as juveniles (e.g., Dungeness crabs [*Metacarcinus magister*], sunflower stars [*Pycnopodia helianthoides*] and cabezon [*Scorpeanichthys marmoratus*]) plus additional predation by sea otters (*Enhydra lutis*) and humans. Few sea otters have been documented in the SJA and sparse data exist to suggest other predators as drivers of population declines throughout the state.

Poaching

Poaching, or illegal harvest, may dramatically impact the fate of abalone. Poaching not only directly affects populations, it also makes population dynamics and stock assessments more complicated to understand because the magnitude of poaching is unreported and often difficult to estimate. Furthermore, because poaching is unregulated, it is impossible to ensure that animals have already spawned, or even reached reproductive age, before they are harvested. In such cases, the effects of low population densities are exacerbated and the removal of even a few individuals may have drastic and lasting consequences. Poaching is thus a major threat to abalone in Washington State.

The density of abalone at survey sites in the SJA declined significantly between the 1992 and 2013 surveys. Initially, these declines may have been the combination of both legal and illegal fishing activity, but since fishing was prohibited in 1994, all abalone harvests are now illegal in Washington.

Legal harvest

Harvest estimates from Bargmann (1984) and Gesselbracht (1991) suggest that legal sport harvest of pinto abalone was centered in the SJA and may have been as high as 38,200 individuals per year. The diver self-reported survey may under-estimate true recreational exploitation rates and does not account for cumulative harvest over several decades. This level of harvest may have been too aggressive for populations of abalone in the SJA. The significant decline of pinto abalone density despite complete closure of the fishery in 1994 is not unique to Washington State. Similar pinto abalone population declines have been documented in British Columbia, Canada (Sloan and Breen 1988); where declines continued despite closure of both commercial and recreational fishing in 1990 (Tomascik and Holmes 2003). Current theories suggest that over-aggressive harvests may have depressed populations enough to result in density-dependent reproductive failure.

Environmental change (temperature, salinity, pH, siltation)

While some oceanographic factors such as turbulent surf, unfavorable current trajectories and seasonal variations in conditions (e.g. rainfall, river input) have been drivers of the evolution of abalone for millennia, recent alterations in oceanographic and coastal characteristics may be responsible for increased mortalities, especially during the larval and early juvenile stages of development.

Global concerns have arisen regarding the impacts of environmental change on marine ecosystems (Harley *et al*. 2006). While much of this attention often focuses on large scale phenomena like polar melt, the impacts of changing conditions will be felt at the microscopic level first. A slight increase in temperature and decrease in salinity in the north SJA has been observed (Masson and Cummings 2004) and regional sea surface temperatures in the 1990s were the warmest in recent history (Strom *et al*. 2004). How such changes affect marine ecosystems can be better understood through the use of controlled experiments, in this case, with pinto or other species of abalone.

Temperature has been shown to both directly (e.g. disease expression) and indirectly (e.g. food availability) affect abundance in other abalone species (e.g. Vilchis *et al*. 2005). An effect of temperature increase on pinto abalone would be more likely observed in shallow aggregations, yet survey data reveal more rapid declines among index sites at deeper depths (Rothaus *et al*.

2008). Meanwhile, studies of the effects of different temperatures on larval development reveal that pinto abalone larvae tolerate a relatively broad temperature range (Bouma 2007; Friedman *et al*. unpublished data).

Marine waters entering the Strait of Juan de Fuca, the Puget Sound and the SJA are mixed with numerous freshwater inputs. Salinity may prove to exert great influence on recruitment; low salinity has been shown to reduce larval and post-larval survival (Bouma 2007). Crim *et al*. (2011) found that larval development of pinto abalone was affected by ocean acidification conditions. Larval survival decreased and shell abnormalities occurred under experimentally elevated pCO2 conditions. Ocean acidification and low salinity may impede recruitment in marine invertebrates (e.g. Wootton *et al*. 2008) but more studies on temperature, salinity, and pH effects on pinto abalone abundance are necessary.

In addition, elevated sedimentation and levels of pollutants may be affecting reproduction, settlement and juvenile survival. The direct effects of increased levels of pollution on abalone in Puget Sound have been poorly studied or documented, but suspected impacts on other species within the region are well documented (e.g., Orcas, kelp [Springer *et al*. 2007], eel grass). Such anthropogenic inputs may include not only toxins, but sediment and nutrient fluxes that may block light or create eutrophic conditions in coastal systems.

Disease and parasites

No disease impacting wild pinto abalone has been reported in Washington State. However, *Labyrinthuloides haliotidis*, a protistan parasite lethal to juvenile abalone, caused catastrophic losses of cultured pinto abalone in British Columbia, Canada in the early 1980s (Bower 2003). A disease screening of 15 wild adults collected from the SJA in 2003 revealed no signs of disease (C. Friedman, unpublished data). Annual whole health hatchery screenings of adults and juveniles from 2009-2013 have found no OIE reportable diseases in Washington pinto abalone (C. Friedman, unpublished data). A disease that affects only young wild abalone remains a possibility, but no work has been done to test this hypothesis.

An additional lethal disease of note is Withering Syndrome, caused by a bacterial infection that resulted in precipitous declines of black abalone in California and is related to variable levels of losses in other wild and farmed abalone species (Crosson *et al*. 2013; Friedman *et al*. 1997; 2000; 2002). The population effects of Withering Syndrome appear to be largely restricted to the warmer waters of California (Altstatt *et al*. 1996, Raimondi *et al*. 2002, Friedman and Finley 2003, Miner *et al*. 2006). Outbreaks of the disease among populations that were already compromised by overfishing have been included as factors in the eventual listing of two species under the ESA.

More recently, a previously unknown herpes virus, Abalone Ganglioneuritis Virus (AVG), was observed in abalone farms in southern Australia (Hooper *et al*. 2007) and spread to adjacent wild stocks, causing catastrophic losses to both farm and wild abalone populations (Hooper *et al*. 2007; OIE 2012; Crane *et al*. 2013). Unlike withering syndrome which has a long incubation period, this virus caused 100% mortality in experimental trials within 1-2 weeks and resulted in near complete losses in several abalone farms and up to 80% losses in adjacent wild stocks in Victoria, Australia (Hooper *et al*. 2007; OIE 2012; Crane *et al*. 2013). A similar herpes virus has caused similar losses in farmed abalone in Taiwan (see OIE 2012). Given the catastrophic effects of this disease on abalone populations and other previously unknown diseases, attention to avenues of importation of exotic abalone species is needed (e.g. those destined for human consumption or bait that may come into contact with Washington state waters).

Sabellid polychaetes affect abalone shell growth, and they were introduced to abalone in the United States from South Africa (Fitzhugh and Rouse 1999, Kuris and Culver 1999; Culver and Kuris 2004). This introduction highlights the sensitivity of abalone to threats that may not already exist. A disease outbreak among the remaining populations of abalone in Washington State could cause irreversible damage to already struggling populations and highlights the need for careful screening and thoughtful consideration with respect to all handling of animals.

Actions Already Completed or Underway

Pinto abalone fishery and status in the Pacific Northwest

Late 1970's: Canadian commercial fishery peaked at > 400 metric tons per year.

1980: Surveys estimated the Washington State recreational fishery harvest at nearly 40,000 abalone per year.

1990: Canadian fishery closed to all user groups due to population concerns.

1992: On-going, WDFW survey program initiated, to include ten index sites in the SJA known for their historical abundance of abalone.

1994: Washington State recreational fishery closed.

1996:

- Alaskan commercial fishery closed.
- WDFW designated pinto abalone as a "Sensitive Species" and they were added to the State Candidate Species List.

1999: Northern (Pinto) abalone designated as "Threatened" by the Canadian Committee for the Status of Endangered Wildlife.

2003: Federally listed under Canada's Species at Risk Act.

2004: Federally listed in the U.S. as a Species of Concern.

2006: Listed as "Endangered" under IUCN red list.

2009: Listed as "Endangered" under Canada's Species at Risk Act (SARA).

2013:

- NDRC submitted a petition to NOAA to list pinto abalone as "Threatened" or "Endangered" under federal ESA.
- Center for Biological Diversity submitted a petition to NOAA to list pinto abalone as "Threatened" or "Endangered" under federal ESA.

Meetings and funding for pinto abalone in the Pacific Northwest

1999: International workshop on rebuilding abalone populations in British Columbia (Campbell 2000).

2002: Washington Sea Grant funded UW to initiate studies on pinto abalone population status and development of culture methods.

2003:

- UW established a restoration hatchery for pinto abalone at the NOAA Mukilteo Biological Research Laboratory.
- American-Canadian meeting held for abalone conservation and recovery.
- Saltonstall-Kennedy funded UW to optimize pinto abalone rearing methods, field assessment of populations and genetic characterization of Washington abalone (Straus and Friedman 2009, Straus 2010).

2004: Washington Sea Grant funded UW to assess larval behaviors, settlement competency, and recruitment (via recruitment modules, Bouma *et al*. 2012) and to develop a molecular assay for larval abalone detection (Vadopalas *et al*. 2006).

2006: SeaDoc Society funded UW to initiate genetic studies to refine pinto abalone taxonomy in the Puget Sound – Georgia Basin region (Straus 2010).

2007:

- WDFW funded one full time employee as hatchery program biologist.
- SeaDoc Society funded juvenile abalone outplant.
- SeaDoc Society facilitated Canada-US abalone meeting.

2008:

- SeaDoc Society funded aggregation studies as a method for restoration/recovery.
- NOAA Species of Concern Program funded UW to study the reproductive success of genetically distinct abalone. This study investigated hybridization between pinto and flat abalone.
- Northwest Straits Initiative funded outreach materials (posters and website).
- PSRF funded part-time hatchery technician for Port Gamble facility.
- The Russell Family Foundation funded abalone restoration efforts.
- PSRF invested in abalone recovery via larval and juvenile outplant and outreach.
- WDFW funded one full time employee as a hatchery program biologist.
- WDFW funded a student intern for the abalone hatchery program under the Shewmaker endowment.

2009:

- NOAA Species of Concern Program funded investigations of aquaculture rearing techniques and outplanting methods (Stevick 2010).

- Trans-boundary abalone working group meeting.
- WDFW funded one full time employee as hatchery program biologist.
- WDFW funded a student intern for the abalone hatchery program under the Shewmaker endowment.

2010:

- Washington Sea Grant funded ocean acidification work: "Effects of ocean acidification on declining Puget Sound molluscan calcifiers."
- WDFW funded one full time employee as hatchery program biologist.
- WDFW funded a student intern for the abalone hatchery program under the Shewmaker endowment.

2011:

- NOAA Species of Concern Program funded "Abalone Restoration in the Pacific Northwest."
- WDFW funded one full time employee as hatchery program biologist.
- WDFW funded a student intern for the abalone hatchery program under the Shewmaker endowment.

2012:

- Washington Department of Natural Resources funded PSRF abalone recovery efforts: larval outplanting research, PIT tagging studies and field nursery trials.
- WDFW funded one full time employee as hatchery biologist.
- WDFW funded a student intern for the abalone hatchery program under the Shewmaker endowment.

2013:

- "Abalone Restoration in the Pacific Northwest" funding cut in grant year 3 due to federal sequestration.
- WDFW funded one full time employee as hatchery biologist.
- WDFW funded a student intern for the abalone hatchery program under the Shewmaker endowment.

Abalone restoration activities in the Pacific Northwest

1992: WDFW established a system of 10 permanent abalone survey stations, or index sites within the SJA. These sites were chosen based on their historically abundant adult abalone populations.

1994: WDFW surveyed abalone index sites in the SJA.

1996: WDFW surveyed abalone index sites in the SJA.

2000: Canadian pilot projects were initiated to restore abalone populations in British Columbia waters.

2001:

- Bamfield Huu-ay-aht Community Abalone Project (BHCAP) was established in British Columbia.
- Abalone genetics program was initiated to explore population structure and to establish forensic baseline for use against poaching in British Columbia.

2003:

- The first hatchery-raised abalone were outplanted in British Columbia.
- NOAA's Mukilteo facility was established as the hatchery for pinto abalone rearing and restoration studies. The program was maintained full-time by Friedman Lab at UW.
- WDFW assessed 10 abalone index sites in the SJA.

2004:

- A program was initiated to examine the genetic diversity among abalone in the SJA. This study is crucial to ensure that hatchery studies do not diminish the natural genetic structure of populations.
- Recruitment study undertaken in the San Juan Archipelago. Abalone recruitment modules were distributed at different locations and depths throughout the SJA to assess juvenile abalone recruitment. Very low recruitment success was observed and no significant differences were observed among sites and depths (Bouma 2007, Bouma *et al*. 2012). This finding is supported by index site data, which similarly showed very low recruitment.
- WDFW surveyed 5 of the abalone index sites in the SJA.

2005:

- A molecular tool (qPCR assay) was developed for identification and quantification of larvae in water column (Vadopalas *et al*. 2006).
- Experiments were conducted at the NOAA Mukilteo hatchery facility to determine whether abalone behavior (habitat selection and movement patterns) differed between habitat-enriched and conventional rearing tanks. Results indicated that rearing conditions can affect abalone behavior and should be a consideration when developing restoration efforts (Straus and Friedman 2009).
- WDFW surveyed 5 of the abalone index sites in the SJA.

2006:

- Mesocosm and microcosm studies examined the effects of salinity and temperature on larval behaviors and survival. Results demonstrated that developing larvae are highly sensitive to changes in salinity but are relatively robust to temperature variability (Bouma 2007). These studies are important to understanding how changes in the Puget Sound environment may be affecting abalone recruitment.
- Canada's BHCAP began selling their first hatchery-raised abalone.
- WDFW surveyed 10 abalone index sites in the SJA.

2007:

- WDFW observed a 77% decline at index sites in abundance since surveys began 15 years prior (despite closures) (Rothaus *et al*. 2008).
- Length frequencies indicate that populations at index sites are ageing without replacement by new cohorts (Rothaus *et al*. 2008).

- Hatchery-raised, juvenile abalone were outplanted in the Strait of Juan de Fuca to assess natural mortality and to prepare for future, large scale outplants. Results demonstrated that the chance of survival was significantly increased for larger-sized juvenile abalone across habitat types assessed.
- Settlement competency periods were assessed at different temperatures. Results from this study remain unclear.
- J. Bouma was appointed by WDFW to manage the Mukilteo hatchery program full-time. The Friedman Lab at UW continued to support the hatchery program part-time.

2008:

- A second hatchery facility was built in Port Gamble, WA and was stocked with juvenile abalone. The facility was staffed part-time.
- Hatchery-spawned post-larval, newly settled abalone were outplanted in Freshwater Bay, Strait of Juan de Fuca. This study was complicated by low yields of larvae and inconsistent fertilization success in the hatchery. These difficulties illustrated the need for further research in husbandry and reproductive behavior.
- A public outreach campaign was initiated in Washington State to inform the public of population declines. Posters were distributed to dive shops and on the Washington State Ferries, www.pintoabalone.org was launched and a series of public presentations was initiated.
- A broodstock replacement program was initiated by which animals that successfully produced offspring in the hatchery were returned to the wild. These animals were placed into aggregations in the wild in order to boost their reproductive potential and to assess this method as a restoration strategy. Lone abalone in the wild – those that were prohibitively far from other abalone to successfully reproduce – were then collected and rotated into the broodstock population in the hatchery.
- A study of hatchery rearing techniques (conventional aquaculture vs. enriched habitat environments) was initiated.

2009:

- Abalone Recovery Management Plan drafted by collaborators for populations in Washington State.
- WDFW surveyed the two aggregation sites to assess survival.
- WDFW surveyed 10 abalone index sites in the SJA.
- Juvenile abalone (N= 1,130) were outplanted at four sites on Burrows and Allan Islands by WDFW and PSRF.
- Post-outplant surveys were conducted by WDFW at two of the four 2009 outplant sites.
- An experimental outplant of differentially reared juvenile abalone was done in Freshwater Bay by the UW, WDFW and Jamestown S'Klallam Tribe in order to assess the role of rearing method on outplant survival and growth.

2010:

- WDFW and SPMC conducted post-outplant surveys at the four Burrows and Allan Islands sites.
- Post-outplant day and night surveys were done by SPMC and WDFW at an Allan Island site to

compare encounter rates. No differences in abalone abundance were detected between the day and night surveys.

- A one year post-outplant survey was conducted in Freshwater Bay, and no difference in survival with respect to treatment (conventional vs. enriched rearing habitat) was detected (Stevick 2010). Overall survival after one year was 6.6%. Results demonstrated suitability of low density, conventional rearing methods.

2011:

- About 2,100 juvenile abalone from the Mukilteo and Port Gamble rearing facilities were outplanted by WDFW and PSRF at six sites: four existing sites at Burrows and Allan Islands near Shannon Point and two new sites at Low Island in the San Juan Channel.
- SPMC completed post outplant surveys at all six restoration sites (four near Shannon Point and two in the San Juan Channel).
- A joint PSRF/UW study evaluated passive integrated transponders (PIT) as tags adhered to either the dorsal exterior or ventral interior portion of the shell or injected in the foot muscle of abalone in the Mukilteo hatchery. PITs could provide a means to allow easier detection of abalone during surveys. Results indicated that there was no difference in growth and survival among tag location, but PIT retention was greater for shell vs. injected tags (90% vs. 10%, respectively) over a nine month period (Hale *et al*. 2012).

2012:

- The two aggregation sites (artificial aggregations were created in 2008) in the San Juan Islands were surveyed by WDFW and PSRF.
- Post outplant surveys were done by WDFW and PSRF at all six restoration sites (four near Shannon Point and two in the San Juan Channel).
- UW/WDFW/PSRF began characterizing seawater chemistry at the Mukilteo hatchery.
- A UW/PSRF/WDFW study evaluated broodstock conditioning in the hatchery comparing natural vs. artificial light regimes and macroalgal vs. artificial feed regimes. Gonad maturation was enhanced in natural daylight conditions, feed regimes had no impact on conditioning.
- Larval outplant trials with GABA induced settlement on nine gabions at Cypress Island were initiated by PSRF and WDFW.

2013:

- Almost 1000 juvenile abalone from the Mukilteo hatchery facility were outplanted by WDFW and PSRF at two sites at Low Island in the San Juan Channel.
- Ten abalone index sites were surveyed in SJA by WDFW and PSRF researchers.
- UW/PSRF/WDFW continued characterization of Mukilteo hatchery seawater chemistry and noted increasing acidification of local waters.
- UW/PSRF conducted ocean acidification study on pinto abalone. Both parental and larval seawater conditions impacted larval survival (Friedman *et al*. unpublished data).

Knowledge Gaps

Effects of ocean acidification on abalone

Rising atmospheric carbon dioxide concentrations lower the pH of global oceans (Feely *et al*. 2004), increasing concern about the effects of such ocean acidification on the development of marine mollusks (Wootton *et al*. 2008; Shirayama and Thornton 2005). Abalone, like other mollusks, grow a calcium carbonate shell during their early development and the effects of decreased pH on this development are currently being explored. Crim *et al*. (2011) found that shell abnormalities occurred or shell size was reduced for pinto abalone larvae under increasingly acidic conditions in the laboratory. Several critical areas of related study need to be addressed. This includes the synergistic effects of ocean acidification, temperature and pathogens; the immediacy/delay of potential acidification exposure on abalone health, and the role that temperature may play; and the effects of ocean acidification on both broodstock fitness and the quality of their eggs and larvae. Such understanding would inform future restoration efforts and provide a broader understanding of ocean acidification effects on abalone and mollusks in general.

Dispersal dynamics

Abalone are broadcast spawners whose gametes and larvae experience planktonic stages that are crucial for the species' survival and genetic mixing. Dispersal dynamics thus play a critical role in the propagation and perpetuation of abalone populations. As studies proceed that aggregate populations in hopes of boosting natural recruitment, it is pivotal that we better understand these dynamics in order to most effectively position spawning aggregations and in order to set the expectations for such work. If we hope to quantify recruitment success as a function of recovery efforts, we must understand where to expect larval settlement after their 10-14 day planktonic phase. Furthermore, in order to integrate genetic considerations into recovery efforts, we must at least acknowledge current ideologies with respect to abalone metapopulations and dispersal.

Abalone larvae do not feed and they are relatively poor swimmers, so it has been proposed that their dispersal is minimal, ranging from distances <100 m to several kilometers (National Marine Fisheries Service 2009; Shepherd and Brown 1993). It should be noted also that dramatic tidal currents in the SJA may create a unique environment for dispersal as compared to coastal currents. Thus, directed genetic studies may provide more insight into the dynamics for Washington's populations than oceanic models from elsewhere.

Life history data

Species of the genus *Haliotis* are valued worldwide, but for many species there is still a dearth of biological and ecological data. Such scarcity combined with the cryptic nature and patchy distribution of abalone in the wild makes the species difficult to study and even more difficult to manage. With better life history data for each species comes a better understanding of the species' reproduction and growth characteristics. This will lead to a better understanding of how populations may be affected by particular threats and how such vulnerabilities may be specifically targeted by restoration strategies.

Our ability to recover pinto abalone populations would benefit greatly from a better understanding of:

- Movement/migration distance at each post-settlement life stage
- Maximum age
- Age/size at reproductive senescence
- Survival rates at each life stage
- Effects of water quality on various life stages

RECOVERY

WDFW lacks the necessary resources to conduct extensive surveys as have taken place for other species of threatened or endangered abalone along the west coast (e.g., white abalone). While our understanding of the species would benefit greatly from expanded surveys, existing data from Washington (Rothaus *et al*. 2008; WDFW unpublished data) have enabled us to conclude that: 1) based on an increasing mean shell length in surveyed populations and lack of juvenile abalone, successful recruitment is not occurring (populations are aging without replacement), and 2) densities of abalone in Washington are likely too low to allow sufficient reproductive success for population recovery or growth. These data-based findings lead us to conclude that wild abalone populations in Washington State are unlikely to recover without human intervention including supplementation.

Recovery Goal

The overall, long term goals of the Washington State Abalone Recovery Plan are to halt the decline of abalone stocks in the Pacific Northwest and to return the population to a self-sustainable level. Given that fishing prohibition and 20 years of recovery have failed, abalone aggregation and supplementation are key current activities identified as necessary to reach our overall goal. Collaborative restoration efforts so far have been scientifically methodical and have followed the primary principle of “do no harm”. Washington restoration strategies follow the American Fisheries Society (Williams *et al*. 1988) and the World Conservation Union (IUCN 1998) guidelines for re-introduction of endangered or threatened species.

Pinto abalone in Washington State will be considered ‘recovered’ when the threat of extirpation no longer exists and both the population size and the local densities of abalone aggregations have reached levels that are self-sustainable. Determination of a population’s sustainability will be based on quantitative estimates of recruitment (number of emergent individuals entering a population), nearest neighbor (proximity of individuals to one another and reproductive aggregations) and population density (number of animals per unit area).

Insufficient biological and ecological data exist for determining the minimum density threshold needed for pinto abalone populations to be at self-sustainable levels. Generally, broadcast spawning, sedentary invertebrates, such as abalone, must be aggregated above a minimum density range of 0.15 to 0.30 individuals m^{-2} for successful fertilization and prevention of population collapse (Babcock and Keesing 1999). We use this mature adult density range as a minimum target for guiding our recovery estimates. Until populations exceed this critical threshold density range (or until above a critical density specifically characterized for pinto abalone) they will be considered at risk of recruitment failure, and ultimately, extirpation.

Recovery Feasibility

Critical habitat for pinto abalone is not well defined nor quantified in Washington. Recovery of pinto abalone is achievable if successful reproduction and/or recruitment are not suppressed by extrinsic factors such as global warming, ocean acidification and illegal harvest. Suitable habitat does not appear to be limiting; we have realized a successful juvenile outplant with relatively high survival (12.5% after 1 year for juveniles outplanted at 8-45 mm). Protocols now exist to successfully spawn and rear pinto abalone while maintaining high genetic variability in the population. The feasibility of outplanting larval abalone in Washington is under study and an initial evaluation is planned for 2014.

Population and Distribution Objective(s): Measurable outcomes

We suggest that multiple measurable outcomes are needed to assess the success of recovery efforts on pinto abalone populations. The current scale of supplementation of pinto abalone is experimental and likely sub-optimal to affect a discernible change in population abundance. As supplementation increases, the following criteria could be used to gauge success.

Objective 1 (Short term): Measure increased natural recruitment at aggregation sites. Aggregations of adult abalone in the wild were initiated in 2008, so emergent recruits (50-90 mm) resulting from these aggregations could be observable as early as 2012. We aim to observe at least 2 aggregation sites at which this emergent size class represents ≥ 15% of the total size distribution, similar to the size class proportion observed in 1992, when the current WDFW index sites were first established.

> Preliminary results for Objective 1: In 2012 the two aggregation sites were surveyed and a total of 39 live pinto abalone were observed. Of these animals, 8 had shell lengths <90mm, or about 20.5% of the total number observed were in the emergent size class.
>
> A follow-up survey was conducted in 2013 at one of the two aggregation sites. In 2012, this site had 4 emergent size class abalone (defined as <90 mm SL) out of 26 abalone observed, or 15.4% emergent size abalone. In 2013, this same aggregation site had only 1 emergent size class abalone out of 27 abalone observed, or 3.7% of the total number of individuals

observed. It is not known if the observed decrease in recruits represents emigration or mortality.

Objective 2 (Medium term) – At least 50% of index sites reveal size distributions where the emergent size class (50-90 mm) represents ≥ 15% of the total size distribution.

Objective 3 (Short-term) – For a given aggregation site, the proportion of animals aggregated after one year is ≥ 0.5. This means that at least 50% of animals placed on the aggregation site are present one year later.

Preliminary results for Objective 3: In the Fall of 2012, 21 adult abalone with PIT tags embedded in their shells (mean SL = 123.8 mm) were released at an aggregation site designated GR. This was in addition to abalone already present at this site. Six months later, in the spring of 2013, the GR aggregation site was surveyed and 11 live abalone with PIT tags were encountered, or 52.4% remained on or near the aggregation site. A total of 4 PIT tagged shells were recovered, or 19.0% of the animals outplanted. All shells that were recovered were about 3 mm larger than the outplant size (SL); growth suggests that handling stress was unlikely to have been a primary cause of mortality. Six of the PIT tagged abalone were not encountered, or 28.6% of the original number of 2012 outplanted abalone, indicating that live animals or dead shells were cryptic or emigration from the plot had occurred.

Objective 4 (Medium-term) – For a given index site, the proportion of animals observed to be aggregated during a survey is ≥ 0.5. This means that at least 50% of animals on the aggregation site have a nearest neighbor distance of less than 1 meter.

Objective 5 (Medium-term) – For non-index site surveys, the number of reproductively isolated abalone – defined as an adult abalone that is found at a distance > 15 m from the next nearest abalone – is less than the number of adult abalone observed to be aggregated.

Objective 6 (Short-term): Observed heterozygosity of individuals in created aggregations shall be > 0.7 (Observed heterozygosity of wild British Columbia abalone populations range from 0.73-0.891 [Withler *et al*. 2003; Lemay and Boulding 2009]).

Objective 7(Medium-term): Mean shell length (SL) of animals observed at index sites has decreased to the mean shell length of animals during the 1992 survey (SL=105.3 mm).

Objective 8 (Long-term): Mean shell length (SL) of animals observed at index sites has decreased to the mean shell length of animals during the 1979 survey (SL=97.6 mm).

Objective 9 (Medium-term): Using genetically diverse cohorts, continue seeding juvenile outplant sites until we observe an emergent, mature spawning population at a density above $0.30/m^{-2}$.

Approaches Recommended to Meet Recovery Objectives

In order to meet the above objectives, a multi-faceted education, restoration and management approach will be required, including:

- Maintain fishery closures for pinto abalone throughout the state.
- Increase enforcement by WDFW of the closure, including increased penalties for poaching.
- Continue education and outreach for recreational and commercial divers, waterfront property owners, and boaters.
- Continue index site monitoring.
- Create artificial aggregations using reproductively isolated wild adult abalone.
- Reintroduce broodstock animals to the wild in aggregations after successfully spawning in the hatchery.
- Identify seawater conditions that impair survival, reproduction, and recruitment.
- Improve abalone husbandry/rearing techniques to increase the production of genetically diverse hatchery progeny.
- Maximize parental crosses and number of distinct families within the constraints of hatchery holding capacity by using single parent crosses and a partial factorial matrix spawning design. Juveniles from the families produced will be outplanted to boost recruitment in the wild.
- Identify the most efficient outplant size based on results of juvenile outplant study versus the costs of rearing animals to a particular size.
- Implement a citizen-based, volunteer component that expands education, awareness and participation from within user and community groups.
- Expand studies that evaluate the potential effects of climate change and ocean acidification on abalone recruitment and mortality (laboratory-based manipulation of temperature, salinity, pH).
- Resolve uncertainty in the causes of broodstock mortality and identify hatchery methods that result in the highest survival of animals in the face of changing ocean chemistry and temperature.

Available Abalone Recovery Strategies (Table 2):

- Do nothing
- Increase enforcement
- Aggregation
- Translocation
- Outplants of larval and juvenile abalone
- Marine protected areas
- Field nurseries
- Expanded husbandry
- Expansion of monitoring
- Tagging studies
- Modeling

1) *Do nothing.*

This strategy assumes continuation of current fishery closures but would involve neither hatchery-based supplementation nor manipulation of wild abalone stocks. In order for populations to be sustained, this strategy assumes that abalone are highly fecund broadcast spawners whose population densities are still high enough to sustain natural recruitment at sufficient levels. It is possible that populations may experience large natural fluctuations and as long as poaching does not account for substantial changes in the current cycle and changes in ocean chemistry and temperature do not impair abalone survival and recruitment, populations could recover on their own.

Even under a “do nothing” approach, assessment will be required to gauge changes in population abundance. In addition to continuation of the abalone monitoring index sites, additional timed swim surveys may be a valuable contribution to the current protocol. Permanent transects may undergo habitat changes that affect populations at those sites, while ensuing recruitment dynamics may yield variability in other habitats or regions that would not be otherwise captured. An example may be behavior adaptation of abalone to deeper waters or adjacent areas to avoid nearshore physical and chemical marine water changes (increased freshwater run-off, increased ocean acidification, etc.). Currently established index stations at fixed locations and water depths would be unable to detect this type of change in horizontal or vertical distribution.

2) *Increase enforcement*

WDFW increases the enforcement of the fishery closure and increases penalties for poaching. This strategy would also include implementing designations for pinto abalone that require such enforcement and/or fines. Increased enforcement of other dive fisheries (such as sea urchin, sea cucumber and scallop fisheries) would have the added benefit of assessing illegal harvest of abalone.

3) *Aggregation*

Populations of abalone in Washington are likely no longer sufficiently abundant to reproduce successfully and a potential strategy for ameliorating this condition may be as simple as locating reproductively isolated individuals (within Washington) and relocating them in sufficiently dense aggregations.

Benthic marine invertebrates exhibit decreased reproductive success as density decreases (Levitan 1991; Yund 1995) and as distance between spawners increases (Pennington 1985; Yund 1990; Levitan *et al*. 1992). In addition, abalone aggregation (both percent clustered and cluster size) has been found to increase with overall density (Shepherd and Partington 1995). Populations with densities below 0.15-0.30 abalone/m^2 have been considered at risk of recruitment failure and collapse (Shepherd and Partington 1995; Shepherd and Brown 1993), and corresponding male-female nearest neighbor distances at these densities were between 1 and 2 m (Babcock and

Keesing 1999). While it may be possible that potential Allee effects at low abalone densities might not demonstrate threshold tendencies as previously described (see Lundquist and Botsford 2004), it is still valuable to use these minimum density ranges for successful fertilization as a guide when making decisions about artificial aggregation and outplant density.

The current paradigm assumes that the genetic composition of extant populations in Washington represents that of a 'healthy' abalone population. Therefore, by aggregating individuals from within the local population, we may boost the reproductive potential of each individual while maintaining adaptedness. It is possible however that a factor in the decline of abalone populations is related to a deleterious genetic component that will be propagated by and impede the success of aggregation efforts. This latter scenario, if true, would arguably mimic what would occur naturally without aggregation.

If aggregations formed as part of our restoration efforts reveal a lack of recruitment success, it will inform and guide future restoration strategies. For example, it may justify the translocation of conspecifics from other geographic regions, perhaps as a reciprocal transplant, to identify whether recruitment failures might be attributed to extrinsic factors (e.g. salinity, temperature, pH), genetic factors, or other as of yet unidentified origins.

One indirect artifact of the aggregation process is that, to avoid discovery by poachers, the aggregation studies are being conducted in locations that are not typically frequented by fishers and recreational divers. Thus, potential concerns about the habitat and ecosystem differences of these inadvertent refugia should be evaluated in conjunction with the efficacy of the studies themselves. For example, what are the habitat characteristics that make these sites less attractive to divers and fishers, and could such missing (or additional) characteristics affect the outcome of aggregation success?

Artificial aggregations are believed to have a reasonable likelihood of success and are currently being undertaken on a pilot scale in the SJA. If positive results cannot be ascertained within five years, use of this strategy should be re-evaluated.

4) *Translocation*

This strategy relies on supplementing extant populations with individuals from historically and geographically isolated populations in Alaska and/or Canada. The basis of this strategy lies in bolstering genetic diversity and the number of reproductively mature individuals in local spawning populations, and thus increasing the likelihood of reproductive success. Translocation studies have been done in California with pink and green adult abalone with evidence of success before poaching occurred (Henderson *et al*. 1988; Tegner 1992, 1993, 2000). Emmett and Jamieson (1989) moved 50-100 mm pinto abalone from exposed sites where growth is slower to two sheltered sites and after 9 months, observed 32% and 72% survival and enhanced growth. Concerns related to translocation strategies include: 1) Transfer of disease between/among populations; 2) Disruption of genetic structure; 3) Survivorship of outplants; 4) Poaching among recently transplanted populations.

Under the assumption that local populations are genetically 'healthy', the introduction of individuals from a distant population may have deleterious consequences if they change patterns of local adaptation. However, given that successful natural recruitment is not being observed among Washington's abalone, it could be argued that 'foreign' spawners may provide beneficial genetic change by increasing genetic diversity. Furthermore, if transplants come from areas with high densities of abalone, they may be behaviorally conditioned to be more cryptic, allowing them to better avoid would-be poachers as well. The translocation strategy would require strict adherence to the do no harm principle with close scrutiny of genetic and potential disease risks.

A conservative approach to translocation would be a pilot scale transplant to assess the relative natural mortality of these individuals versus those of native aggregations. If survivorship of adults is comparable and these adults are capable of spawning effectively within the SJA, important information could be gleaned with respect to 1) the relative health of local abalone (if, for example, translocated abalone demonstrate higher survival than local individuals then populations may benefit from inter-breeding with translocated individuals); 2) the potential presence of environmental barriers (if neither translocated nor local populations exhibit recruitment, extrinsic factors may be driving observed patterns).

Conclusions drawn from studies of translocated individuals are difficult to control because increased mortality or decreased recruitment could be effects of handling or relocation. However, because of the restoration motivation of this work, an absence of controls in the event of a positive result may still be deemed successful and useful.

If positive results cannot be ascertained within five years, use of this strategy should be re-evaluated.

5) *Outplants*

Outplants of hatchery reared abalone have been conducted worldwide (for review see Tegner & Butler 1989; McCormick *et al*. 1994, Heasman *et al*. 2004) and survival rates of the seeded abalone have varied greatly (see Table 3). Several studies (Rothaus *et al*. 2008; Bouma *et al*. 2012) have identified recruitment failures in the SJA and are suggestive that hatchery-based supplementation of wild populations will be necessary for abalone to persist in Washington State. Efforts to supplement abalone populations worldwide must be evaluated not only in terms of their efficacy but also in terms of their resource requirements. Several outplanting experiments have demonstrated that outplanting larger juvenile abalone will increase survival (D. Rothaus *et al*. unpublished data; Stevick 2010; De Waal and Cook 2001; Saito 1984). However, time in hatchery is directly related to the cost of each outplanted individual.

While the ideology behind outplanting is the same for all sizes of animals outplanted, methods may vary substantially, such that for our purposes, we discuss it as two different restoration strategies.

a) 'Larval' outplants

As used herein, the term 'larval' with respect to outplants may be used to include true abalone larvae (i.e. abalone whose developmental stage is between a fertilized egg and pre-settlement, ~0-10 days old) and animals that are actually settled juvenile abalone (~0-30 days post-settlement). These animals are described collectively as we explore methods that yield the lowest mortality.

'Larval' outplants have been attempted for abalone restoration and ranching purposes in many studies, and have shown a range of success in outplant survival rates (0.02-10%; Tong *et al*. 1987; Schiel 1992; Preece *et al*. 1997; Shepherd *et al*. 2000). These studies continue to be attempted because the relative costs of outplanting at such early stages are nominal when compared to outplanting after being reared in a hatchery. Furthermore, outplanting animals early in their development eliminates the risk of hatchery selection and habituation. In hatcheries, mortality observed between early larval stages and the first few months has been reported to be routinely in excess of 10% (Roberts 2003); larval mortality would be expected to be even higher in a natural setting. This generally high mortality compounded by the stresses of the outplant procedure itself suggests low expected yields for larval (and early life history) outplanting.

Larval outplants also result in the propagation of large numbers of full and half siblings in the same location, potentially increasing the long-term genetic risks of inbreeding depression. This risk can be reduced through repeated outplants from multiple families at the same location. Such small animals are impossible to physically tag (with traditional methods). To identify them as hatchery individuals after they emerge, genetic, trace element or other methods could be used to determine parental lineage.

b) Juvenile outplants

This strategy makes use of hatchery grow-out facilities to rear juvenile abalone to a desired size before they are outplanted. Survival of cultured juvenile abalone has varied by species and location, ranging from 0% to 72.4% over multiple year evaluations (Table 3). Studies in Washington State show that survivorship of outplanted abalone is higher for larger individuals. At four trial sites (Freshwater Bay, WA), juveniles 25 mm or greater shell length at outplant had 22.0 % survival after one year (n=132), whereas juveniles less than 25 mm SL had a 3.9% annual survival rate (n=154) at the same sites

(WDFW unpublished data; Stevick 2010), which is in accord with studies for two other abalone species that showed initial size is important for outplant survival (De Waal and Cook 2001; Saito 1984). Large scale outplanting could be undertaken after reared individuals reach the size determined – by such pilot studies – to be most efficient for outplant.

It has been noted however that size-dependent mortality is likely to vary among sites and should be assessed at proposed outplant locations due to habitat heterogeneities (e.g., hydrodynamics, substratum, predator composition and food supply (Roberts 2003)). Each of these habitat characteristics is also likely to undergo temporal dynamics that should be incorporated into outplant timing.

Depending on the size at which juveniles are outplanted, they can be relatively easily tagged. With tagged individuals, outplant sites can be readily populated according to genetic pairings/families. Physical tags also make identification of outplanted abalone easier, although tag retention and longevity are ongoing issues. Tags have been known to fall off or become illegible due to abrasion or biofouling over time.

If size at outplant proves to be indicative of survivorship (e.g. Lapota *et al*. 2000), then the optimal size at outplant will have to be determined by a balance between survivorship and the resource demands to rear abalone to a particular size. It may prove more efficient to rear and outplant a greater number of animals at a smaller size to reduce nursery costs. Roberts (2003) for example, suggested that raising animals to 2-3 mm SL prior to outplant could provide a cost-effective method to boost survival. Alternatively, models may demonstrate that raising fewer animals to larger sizes is a more efficient strategy overall. A cost-benefit evaluation is necessary before juvenile outplants proceed on a larger scale.

A concern with outplanting animals after extended durations in a hatchery is that animals can exhibit behavior that differs from their wild conspecifics. Studies have found that hatchery abalone behavior may differ from wild abalone in terms of habitat selection (Tegner and Butler 1989), susceptibility to predators (Schiel and Weldon 1987) and movement patterns (Schiel and Weldon 1987), which could ultimately influence their survival rates if outplanted to the wild. Straus and Friedman (2009) determined that habitat selection and predator avoidance behavior in pinto abalone differed between abalone reared in conventional tanks and those reared in habitat enriched tanks, however, Stevick (2010) found that similar rearing conditions did not influence outplant survival over 12 months in the field.

6) *Marine protected areas (MPAs)*

MPAs may be the most politically charged of restoration strategies and are unlikely to be utilized for the protection of abalone alone. MPAs often require a great deal of time to be designed, delimited and implemented. They also require costly enforcement, continued community support and they take time to work. However, if enacted they likely provide greater refugia from poaching than a fishery closure for a single species alone.

In the SJA, MPAs have been in place for several years, but abalone are rarely observed within these reserves (Kevin Britton-Simmons, personal communication). While they may receive greater protection from poachers, it is possible that protection of rockfish or other natural predators has increased predator concentrations, thereby negatively impacting abalone populations in reserves. In California however, MPAs have shown significantly higher abundances of abalone than adjacent non-protected areas (Rogers-Bennett and Pearse 2001), though the comparison of these areas may be difficult because they were in place prior to the precipitous declines of some species. In such a situation, it may be necessary for abalone populations to be enhanced prior to MPA implementation.

Technically, all of Washington is already protected against pinto abalone harvest, since all pinto abalone fishing is closed. The level of protection should increase with formal MPAs that exclude other types of harvest activity in the same habitat (such as areas closed to sea urchin and sea cucumber harvest).

7) *Field nurseries*

The use of field nurseries could provide cost-effective intermediate grow-out conditions for abalone that have been weaned onto macroalgae but have not yet reached optimal outplant size. This strategy would help address space limitations at the Mukilteo hatchery. Pilot field nurseries could engage and involve shoreline property owners and marine facility partners, which would build greater community support and awareness for abalone recovery efforts.

8) *Expanded husbandry*

Hatchery programs are resource intensive and are expensive to operate. For the sake of our efforts, costs can be translated to the amount of money required to raise an individual abalone to a certain size, or dollars per abalone per millimeter. Such costs must include not only the amount of money required to raise an individual abalone (e.g., water heating/cooling, food, grow-out space, personnel), but they must include the costs of spawning and fertilization as well.

Consistent broodstock conditioning, induced spawning and fertilization success, and broodstock survival have posed challenges for hatchery staff as abalone restoration work has been developed at the Mukilteo hatchery facility. A greater ability to understand these challenges, as will be ascertained from expanded studies in the hatchery, will increase the efficiency of our efforts and reduce the long term costs (and the associated cost per abalone per millimeter). Furthermore, this increased efficiency will help to maximize the number of distinct families produced within the hatchery.

The ultimate goal of hatchery outplants for restoration is to increase the population density of genetically diverse animals in the wild to a level where natural recruitment becomes self-sustainable once again. The sooner outplants begin to spawn in the wild, the sooner populations are likely to rebound. Furthermore, the sooner we outplant abalone from the hatchery, the sooner those animals are no longer dependent upon costly hatchery resources. However, as discussed in the outplanting section (above), studies are underway to identify the optimal size of animals at outplant to minimize mortality. Thus one of the most valuable husbandry advances would be to increase the growth rate of abalone in the hatchery, provided this strategy does not compromise genetic diversity.

9) *Expansion of monitoring*

One of the major impediments to better understanding the population dynamics of abalone in Washington is the scarcity of data. The current network of index sites is critical to our assessment of populations of abalone and their recent decline, but an expansion of these data may improve upon the knowledge necessary for restoration. Timed swim surveys enable divers to move beyond quadrats and permanent transects, covering more ground and observing a greater diversity of habitat. While these techniques may be less effective for finding the especially cryptic younger abalone, they may be successful in identifying previously unidentified aggregations of adults or more recently recruited aggregations of juvenile abalone. Monitoring different depths should also be implemented to rule out the possibility that abalone are seeking depth refuge from changes in nearshore habitat (such as increased freshwater input, temperature changes, sediment accumulation, etc.).

10) *Tagging studies*

The pilot outplant of juvenile abalone in 2007 was the first mark-recapture study of abalone conducted in Washington. However, since it was confined to experimental plots for a period of one year, it can offer only preliminary data on growth rates and mortality. PIT tagging offers great promise to positively identify individual animals over longer time periods than is possible with physical tags (Hale *et al*. 2012). A commitment to tagging animals during our restoration efforts (broodstock rotation, large-scale outplants, etc.) will provide data on growth rates and recapture and survival estimates.

11) *Modeling*

We have identified the major goal of our abalone recovery efforts to be the achievement of self-sustainable levels of population density. However with sparse information on the population dynamics of pinto abalone in general, and even sparser data on pinto abalone in Washington, our understanding of abalone ecology with respect to ‘long term self-sustainability’ is guesswork at best. While our restoration strategies continue to advance our understanding and ability to propagate and perpetuate abalone in the wild, modeling efforts should be undertaken to advance our understanding of how strategies may best be focused towards our long-term goal of sustainability.

While abalone recovery will ultimately benefit from population viability analyses (PVAs) that can include both deterministic and stochastic modeling frameworks (National Marine Fisheries Service 2008), preliminary modeling should, at the least, include elasticity and perturbation analyses. Critical evaluation of such analyses for vital rates (e.g., fecundity, age at maturity, juvenile survival, adult survival, size at maturity) can help to target management and recovery strategies towards the life history stages that have the greatest effects on population growth (Rogers-Bennett and Leaf 2006; Crouse 1987).

The combination of these size/stage -structured modeling approaches will enable the pinto abalone recovery team to understand population dynamics and extinction risk and how they relate to different restoration strategies and long term conservation goals. Given the data scarcity that currently exists for pinto abalone, using analyses and vital rate data available from other species (e.g., Heppell *et al*. 2000) and from hatcheries, will enable at least precursory analyses for pinto abalone. White abalone (*H. sorensi*), for which arguably less data exist than for pinto abalone, were approached with elasticity analyses to identify adult animals as the most valuable life history stage for targeted restoration efforts (Rogers-Bennett and Leaf 2006). Similar findings for pinto abalone may suggest that translocation and aggregation or larval settlement *in situ* are more immediate priorities than juvenile outplants.

Implications of Restoration Efforts

Restoration efforts are being conducted with the best intent, but as with any human intervention, there are potential, important consequences that should be considered. Disease, genetic, assessment and outplant methods need to be designed to minimize or eliminate any negative environmental impacts associated with the re-introduction of abalone. It is important to also consider ecological interactions that affect other species through trophic cascades related to ‘reintroducing’ a primary consumer.

Table 2. Potential restoration strategies and some of their characteristics

Possible methods	**Likelihood of success**	**Pros**	**Cons**	**Needs**	**Costs**	**Time to measure outcomes**	**Measurable outcomes**
Do Nothing (closure only)	Low	· Low cost	· Recovery unlikely without intervention	· Continued monitoring	· Annual surveys	· 10 + yrs	· Same as current survey set-up
Fishery closure + increased enforcement	Low	· Unlikely, but potentially high impact	· Relatively unlikely to have an impact · Without increased recruitment, population declines still imminent · Increased enforcement may be effective without being measurable	· Increased budget	· Personnel and vehicles	· Immediate	· Number of poachers caught
Outplant larvae/ recently settled post-larvae*	Low – Med	· Lower cost than raising to juvenile · Lower risk of disease from hatchery · Less captive habituation	· Long time to determine efficacy · Genetic controls are difficult (potential for in-breeding) · High mortality · Historically unsuccessful · Difficult to track families	· Hatchery facility & staff · Reliable production of seed · Continued monitoring	· Relatively low · Hatchery spawning time & brief settlement period · Boats/ Divers for outplants · Annual surveys after 2 yrs	· 3 yrs to determine mortality/survival · 6-8 yrs to determine new recruitment	· Count emergent abalone after 3 yrs

Table 2. Potential restoration strategies and some of their characteristics

Possible methods	Likelihood of success	Pros	Cons	Needs	Costs	Time to measure outcomes	Measurable outcomes
Outplant juveniles (sizes 10 – 50 mm)*	Medium	· Higher survivorship than 'larval' outplants · Easier to measure success	· Rearing expense · Risk of habituation to hatchery conditions · Small size classes are difficult to tag	· Continued monitoring · Grow-out requires more space and food as animals get larger	· Relatively high (size dependent) · Husbandry time & space for grow-out · Diver time for outplants · Annual dive surveys	· Yearly evaluation of mortality/ survival · 1-3 yrs hatchery grow-out · 5-8 yrs to assess new recruitment	· Survivorship · Survivorship as a function of size · Proportion of animals remaining aggregated
Translocation	High	· Increased number of wild, mature animals · Relatively inexpensive · Wild animals have less risk of captive habituation · No hatchery required	· Unknown genetic effects · Removes fecund individuals from other populations · Unknown effects of handling on survivorship · Disease introduction · Lack of controls to assess survival	· Continued monitoring	· Travel, collection, transport and outplant of animals · Annual dive surveys	· Annual aggregation assessments · 3+ yrs to assess new recruitment	· Adult survival · Proportion of animals remaining aggregated · Recruitment
Aggregation*	High	· No hatchery required · Low cost	· Unknown effects of handling on survivorship · Dispersal dynamics may affect locations of aggregations	· Continued monitoring	· Diver surveys for aggregation site ID. · Aggregation of animals · Annual dive surveys	· Annual aggregation assessments. · 3 + yrs to assess new recruitment	· Adult survival. · Proportion of animals remaining aggregated · Recruitment

Table 2. Potential restoration strategies and some of their characteristics

Possible methods	Likelihood of success	Pros	Cons	Needs	Costs	Time to measure outcomes	Measurable outcomes
Aggregation* with rotation of hatchery brood stock	Med-High	· Facilitates genetic objectives of hatchery program · Boosts reproductive potential of animals that are ineffective spawners in the hatchery	· Increased risks of handling mortality · Unknown effects of relocating process on behavior	· Continued monitoring	· Annual dive time to replace brood stock from hatchery & monitoring of post-translocation survival	· Annual aggregation assessments · 3+ yrs to assess new recruitment	· Adult survival. · Proportion of animals remaining aggregated · Recruitment
Outplant emergent adults (>50 mm)	High	· Mature at outplant · Higher survivorship · Easier to control genetics	· Risk of captive habituation · Expensive to raise	· Continued monitoring · Expanded hatchery facility and grow-out capacity	· Highest of all options · Husbandry time and space for grow-out · Diver time for outplants	· 3+ yrs hatchery grow-out · Annual aggregation assessments · 7 – 10+ yrs to assess new recruitment (from initial spawn)	· Adult survival · Proportion of animals remaining aggregated · Recruitment

Table 2. Potential restoration strategies and some of their characteristics

Possible methods	**Likelihood of success**	**Pros**	**Cons**	**Needs**	**Costs**	**Time to measure outcomes**	**Measurable outcomes**
Marine protected areas	Low – Med	· Ecosystem benefits · Easier to enforce than fishery closures alone · Poaching more difficult for MPA than for closure alone · Comparison of effects of aggregation in MPA versus outside (assess poaching)	· Require greater stocks of wild animals to be effective · Politically charged · Slow to implement · Refuge for predators as well as abalone · Larvae may disperse beyond MPA confounding measurable outcomes	· Diver time for outplant / aggregation · Enforcement · Community support · Legislation	· Cost of animal relocation and aggregation · Diver surveys · MPA political process would require time and money, plus initial research to delineate potential site locations	· Dynamics of many species could prolong time before efficacy · More likely to see natural variability in population over longer term · MPA's may be assessed on decadal scales (10-25 yrs min)	· Adult survival · Proportion of animals remaining within aggregations · Recruitment

Table 2. Potential restoration strategies and some of their characteristics

Possible methods	Likelihood of success	Pros	Cons	Needs	Costs	Time to measure outcomes	Measurable outcomes
Expanded, volunteer based dive surveys	Low	· Community investment in protecting abalone · Potential ID of new aggregations or recruitment · Inexpensive method to increase survey coverage · Good P.R.	· Liability · Potential for increased diver knowledge of abalone locations	· Logistical coordination · Coordination for data collection	· Outreach coordinator time	· Immediate data · On-going, as activity is repeated	· Number of new survey locations recorded
Education campaign	Medium	· Educates would-be poachers and those unaware of fishery closure · Makes public more aware of poaching and increases pressure on poachers · Good P.R. · Potentially generates more interest in funding · Even if behavior is unchanged, people still become more educated	· Difficult to quantify success	· Personnel	· Personnel for all aspects · Technology and material costs	· Immediate	· Success is difficult to measure but activities are easily quantifiable

* Pilot study either completed or underway

Table 3. Abalone outplants around the world. N= the number of individuals outplanted. [Adapted from the NMFS White Abalone Recovery Plan, 2008. Includes current literature only through 2010].

Citation	Species (*Haliotis sp.*)	Location	Size range (mm)	N	Survival
Lapota (unpub. data)	*H. fulgens*	Pt. Loma, CA	70-100	200	77% after 2 mo.
Rothaus et al. (unpub. data)	*H. kamtschatkana*	Puget Sound, WA	10-46	281	12% after 1 yr.
Rogers-Bennett & Pearse (1998)	*H. rufescens*	Northern CA	mean 8	50,000	0-0.21% after 2 yrs.
Tegner & Butler (1989)	*H. rufescens*	California	40-80		1% after 1 yr.
Stevick (2010)	*H. kamtschatkana*	Puget Sound, WA	mean 24.6	713	6.6% after 1 yr.
Davis (1995)	*H. rufescens*	California	mean 41	7,200	32% after 1 yr.
Dixon et al. (2006)	*H. laevigata*	S. Australia	mean 28	6,970	0-57% after 9 mo.
Shepherd et al. (2000)	*H. rubra*	Australia	mean 12		16.5% after 1 yr.
McCormick et al. (1994)	*H. fulgens*	Catalina Is., CA	mean 25	8,000	40% after 3 mo.
Lee et. al. (2002)	*H. diversicolor*	NE Taiwan			3.59% - 5.13%
Schiel (1993)	*H. iris*	New Zealand	3-30	80,000	1.2-72.4% over 2 yrs
Kojima (1995)	*H. discus, H. d. hannai, H. diversicolor aquatilis, H. d. diversicolor, H. sieboldii*	Japan	15-40		12-51% over 5 yrs.

Seki & Taniguchi (2000)	*H. discus hannai*	Japan	mean 16.5-24.5	166,000	26.7% after 3 yrs.
James et al. (2005)	*H. rubra*	Australia	10-20	360	9% after 3 yrs.
	H. laevigata	Australia	15-30	480	15% after 2 yrs.

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