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STATUS REVIEW OF WHITE ABALONE *(Haliotis sorenseni)* THROUGHOUT ITS RANGE IN CALIFORNIA AND MEXICO

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U.S. DEPARTMENT OF COMMERCE
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Southwest Region Office

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Explanatory Note

Based on information indicating a major decline in abundance, the National Marine Fisheries Service (NMFS) designated the white abalone as a candidate species under the Endangered Species Act of 1973 (ESA) on July 14, 1997. To establish a basis for NMFS to determine whether white abalone is a threatened or endangered species under the ESA, NMFS contracted with Scripps Institution of Oceanography in August 19913 to conduct a review of the biological status of white abalone throughout its range, including the current and historical impacts to the species. NMFS received a draft status review document from Scripps, in April 1999. In order to obtain an independent peer-review, NMFS requested three non-federal scientists to review and report on the scientific merits of this status review. By August 1999, NMFS received these anonymous reviews. Abalone experts from the California Department of Fish and Game and the National Park Service. and NMFS scientists, also reviewed the document. Subsequently, the authors incorporated these comments into this status review, and submitted the revised final status review document to NMFS on March 20, 2000.

We hope that the distribution of this report. will facilitate further discussion and research on the status of white abalone, but the findings of this report should not be construed. as NMFS's determination as to whether white abalone should be listed as a threatened or endangered species under the ESA. The NMFS will make such a listing determination in the Federal Register.

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Table of Contents

List of Figures

List of Tables

1. Executive summary.

The objectives of this status review were to conduct a review of white abalone: literature, to analyze fishery-dependent and fishery independent data from California and Mexico., to review the history of management and contact managers in both states, to compare assessment surveys and evaluate if they are sufficient to detect trends in white abalone abundance, and finally to determine what factors have affected the current status of white abalone.

A review of existing California and Mexican white abalone literature was completed, including gray literature. As the deepest local species and the: most recently discovered, white abalone have been poorly studied; much must be inferred from the biology of congenerics. This information is incorporated in the text, tables, and figures, and in the reference list at the end of the report.

The history of abalone fishing and white abalone fishing has been summarized for both regions. In California the exploitation of white abalone began in earnest in 1968 and had declined dramatically by 1978. In Mexico, a decline in white abalone harvest has also occurred, but the pattern has been poorly documented. Meetings with fishery bioiogists at the Instituto Nacional de la Pesca and the California Department of Fish and Game allowed access, to unpublished data and reports, and discussions of the white abalone situation.

Fishery independent assessment surveys of white abalone abundance were limited in number, as well as in the timing and spatial coverage. Nevertheless, the results strongly indicate that the density of white abalone has declined by several orders of magnitude in both countries since 1970.

Potential factors that may have limited the current status of white abalone were examined through literature review and analysis of both fishery-dependent and -independent data. We conclude that present or threatened destruction, modification, or curtailment of its habitat or range has not led to decline of white abalone. Factors such as disease, natural predation, and competition were also not likely to have caused the decline. Over-utilization by commercial and recreational, but not scientific and educational, purposes has led to decline, in part due to the inadequacy of historical and existing regulatory mechanisms. No other natural or anthropogenic factors, including hybridization, appear to be affecting its continued existence.

The implications of low population size are discussed, along with factors important for future management of white abalone. We conclude that the best estimate of the total abundance of white abalone in California and Mexico is around 1600 animals. This is less than 0.1% of the estimated pre-exploitation population size. This reduction has occurred in the last 30 years. The current population size and density of white abalone mean that recruitment failure is inevitable, and has probably already occurred in California. The current density of white abalone is too low to allow the fertilization success necessary for natural recovery of the population. While the time to extinction could not be evaluated for white abalone in Mexico, without protection and intervention the white abalone is likely to go extinct in California within 10 years.

2. General introduction to abalone.

Abalone are prosobranch marine gastropods (Cox, 1962). The abalone family is considered to be monogeneric (Brown and Murray, 1992a). The single genus, Haliotis (meaning "sea-ear") is found worldwide and contains about 70-80 species (Lindberg, 1992). California abalone species appear to be a single lineage group (Lindberg, **1992) (Figure** I). The common general name is believed to be derived from the Spanish-American word aulon or aulone (Haaker et al., 1986). The taxonomic classification of abalone is as follows:

Phylum Mollusca
Class Gastropoda
Subclass Prosobranchia
Order Archeogastropoda
Superfamily Pleurotomariacea (abalone).
Family Haliotidae
Genus Haliotis (70-80 species, in about 12- 15 sub-genera groups).

All abalone are benthic and occur on hard substrate. They are relatively sedentary. and generally feed on attached or drifting algal material. In temperate regions, most abalone species are associated with kelps, including Ecklonia, Nereocystis, Macrocystis, Laminaria, and Eisenia. One abalone species, H. cylobates, is found in seagrass beds in southern Australia (Shepherd, 1973; Lindberg, 1992). While primarily shallow subtidal, species are found from the intertidal zone to depths of over 200 m (Lindberg, 1992). Abalone are broadcast spawners, the fertilized eggs hatch into trochophore larvae, which then develop into veliger larvae before metamorphosis and settlement. Growth to maximum size is slow, although time to reproductive maturity may be relatively rapid. Tropical species are small, usually less than 50 mm long, while the temperate species are usually larger, with many over LOO mm. The largest species is the California red abalone (H. rufescens), which reaches a length of almost 300 mm (Lindberg, 1992, p 9).

Abalone have supported valuable fisheries in many parts of the world, however, overfishing of abalone has been a problem in every country where they are harvested (Breen, 1986; Tegner, 1989). These molluscs are slow growing and long-lived, with irregular recruitment. Populations are dominated by older individuals and occur in shallow water near stands of macroalgae in predictable and accessible locations, and undertake minimal movements. These characteristics make abalone vulnerable to rapid depletion (Brcen, 1986). Their high unit value warrants intensive seal-ching, and while some stocks may eventually become commercially unprofitable even with very high prices, recreational fisherman continue to operate without regard for economic outlay (Tcgner, 1989).

Eight abalone species are found along the west coast of North America **(Figure 1;** for all locations in this report see **Figure** 2; **Table 1).** There are five recognized west coast subspecies (Howorth. 1978), three of which are found at Guadeloupe Island, Mexico (pink, black and green). 'The common names of the California species are derived from the color or morphology of the shell (Croker, 193 1). Abalone have separate sexes. Males have white or tan gonads, females have green, and immature animals have gray gonads that arc indistinguishable from the underlying hepatopancreas (Cox, 1962).

Five of the California species grow to a large size and have occurred in densities sufficient to attract the attention of commercial and recreational fishermen. Most of these fishcries are likely to have been possible because of the release in predation pressure due to the harvest of sea otters. Sea otters were eliminated from most of their range by hunting in the early 1800's, which subsequently allowed abalone to reach very high densities,. Historically otters were found throughout the range of the north-east Pacific abalone, from central Baja California through California, and arcing over Alaska to the northern Japanese archipelago (Estes, 1980; Tegncr, 1989).

A decline in abundance of several abalone species was reported in the early 1900's (Edwards, 19 13a, b; Bonnot, 1930; Croker, 193 1). This likely reflected a reduction in the accumulated biomass of shallow water stocks close to population centers, especially in southern California. In other regions abalone continued to support a fishery (Cox, 1962). A second decline in California abalone stocks began in the 1970's, and these stocks are no longer capable of supporting commercial fisheries (Karpov et al., 1998). Commercial and recreational fishing of all California abalone was prohibited south of San Francisco in May 1997 (Karpov et al., 1998; CEQA, 1997). It should be noted, however, that red abalone populations north of San Francisco have supported sustained recreation-only fishing for over fifty years. There is evidence that stock size has increased in recent years, suggesting that abalone stocks can be successfully managed when fishing effort is limited and refugia protect brood stock (Karpov et al., 1998). The effort limitation prohibited the use of compressed air and established daily bag limits but did not restrict the number of fishermen. Estimates from creel surveys indicate that the recreational catch from northern California was about equal to the commercial catch from southern California in the 1970's, and exceeded it in the late 1980's (Tegner 1989, p 410; Karpov et al., 1998).

3. White abalone species description.

The maximum shell length attained by white abalone in California is about 20-25 cm; in Mexico it reaches lengths of 17 cm. The adult is characterized by a mottled orange tan epipodium with foliose epipodial papillae and brown cephalic tentacles. The shell is deeply cupped and lightweight, with a poorly defined or absent muscle scar in the interior of the shell. The three to five open respiratory pores are well elevated above the surface of the shell (Bartsch, 1940; Cox, 1960, 1962; Leighton, 197 1).

Prior to 1940 the species was known to fisherman and scientists as “white abalone” (Croker, 193 1, p 69); it was formally described as a species in 1940 (Bartsch, 1940). This was a late scientific description compared to the other California species, which were described between 40 and 122 years earlier **(Table** 1). There is a possible subspecies of white abalone found at Guadeloupe Island (Mexico), although it has not been described as such (Howorth, 1978).

4. Natural history of' white abalone.

4.1. Habitat and distribution.

4.1.1. Historical distribution.

White abalone were historically found between Punta Abreojos, Baja California, Mexico and Point Conception, California, USA, a range of 8" latitude (Bartsch, 1940; Cox, 1960: 1962). This species was reported to be more common along the mainland coast at the northern end of the range, while in the mid-portion of the California range it was more common on the islands (especially San Clemente and Santa Catalina Islands) (Cox, 1960; Leighton, 1972). This distribution pattern may be related to the lack of suitable habitat along the mainiand coast in the mid-portion of the range, or to overfishing in these more accessible mainland regions. In Mexico at the southern end of the range, white abalone were reported as more common along the mainland coast, but are found at a number of islands, including Isla Cedros and Isla Natividad (Guzman del Proo, 1992; Shepherd et al., 1998).

4. I .2. White abalone stocks.

There are no recognized separate stocks of white abalone, due to lack of information about its dispersal and recruitment. Other abalone species, such as the Australian species H. laevigata, may be composed of up to 300 stocks (Sluczanowski, 1984; Shepherd and Brown, 1993). One attempt to use genetic techniques to identify H. rubra and H. laevigata stocks suggested that many small populations exist (Brown and Murray, 1992b).

4.1.3. Depth range.

The white abalone is a deep-living species, found below sympatric west coast species. They are usually reported to occur at depths of 20-60 m and to be most abundant between 25-30 m (80-100 feet) (Cox, 1960; Tutschulte, 1976). Tutshulte (1976) stated that white abalone increased in abundance between 1.5-35 m, but. offered few quantitative data to support this impression. In surveys in Mexico between 1968- 1970, white abalone were most common between 22.5 and 27 m, but were occasionally found at depths of 10- 15 m (Guzman del Proo et al., 1976; Guzman del Proo, 1992, p. 342, 345). A non-overlapping vertical distribution with red abalone was found where they occurred together in the northern portion of Baja California (Guzman del Proo, 1992, p 345).

Generally, most abalone species are shallow-living, occurring between 0-20m in depth. Exceptions include the Australian southern coast species H. scalaris, which is found to depths of SO m (Shepherd, 1973), and several tropical new world species which are found between 50 and 200 m (Lindberg, 1992, p 15). The Florida abalone, H. pourtalesii, is reported to occur between depths of 100 and 400 m (Howorth, 1978). Thus, the deep-water distribution of white abalone is not unique among abalone species worldwide, but H. sorenseni is the deepest-living of the west coast complex.

4. I.4. Morphology.

The relatively thin shell of white abalone may influence vulnerability to predators. The significance of the lack of a muscle scar is unknown, but may affect attachment strength. Apparently fast growing abalone have less of a muscle scar, and may even fail to develop one (Howorth, 1978, p40). The next deepest-living California abalone species (H. assimilis) also has a weak scar.

4.1 .5. Habitat.

White abalone are found in open low relief rock or boulder habitat surrounded by sand at the depths discussed above (Tutschulte, 1976; Davis et al., 1996). Sand may be important in forming channels for the movement and concentration of algal drift (Shepherd, 1973a), although white abalone are reported to feed less on drift material than congeneric species (Tutschulte, 1976). Common algae in the habitat include the kelps Laminaria farlowii and Agarum fimbriatum, and a variety of red algae. White abalone appear to be restricted to depths where algae will still grow, a function of light levels and substrate availability.

4.1.6. Diet.

White abalone larvae do not feed, instead they obtain nutrients from yolk supplies (Leighton, 1972). After settlement from the plankton, small abalone feed upon benthic diatoms, bacterial films, and single-celled algae that are found on coralline algal substrate (Cox, 1962). As they grow larger the diet changes to attached or drifting brown algae (Tutschulte, 1976). Laminaria farlowiii and Agarum fimbriatum are the dominant brown algae in white abalone habitat at depths of 20-40 m. Tutschulte (1976, p 289) reported that these were eaten in the field by white abalone. Laboratory observations suggested that white abalone also preferred these algae as food over the shallower-living Macrocystis pyrifera, but no food choice experiments were performed (Tutschulte, 1976). They have also been reported to eat elk kelp (Pelagophycus porra) (Cox, 1962). White abalone may be food-limited at the lower edge of their vertical range, but there are no data to support this (Tutschulte 1976, p 33; despite his Fig 5.1, there are no data for the deep water algal or drift abundance in his Chapter 4).

4.1.7. Depth patterns.

Depth distributions for white abalone are poorly known. In the most extensive work on this species, the upper and lower depth limits were not established (Tutschulte, 1976). Transplant experiments (from 30 m to 9 m, no controls) showed that gonad maturation in adult white abalone occurred at shallow depths (Tutschulte, 1976, p 186), suggesting the animals could live and reproduce shallower than they were usually found. Tutshulte attributed the upper limit of white abalone to competition with pink abalone and predation by octopuses on the exposed and fragile shells (Tutschulte, 1976). Predation by sea otters (when the otter and white abalone ranges overlapped) in shallow waters on the less cryptic white abalone may have restricted them to depths below 2.5 m (speculation in Tutschulte, 1976, p 266). White abalone shells are not found in Indian middcns, probably because their depth was too great for them to be captured by the

Indians (Cox, 1960). Thus, it is likely that white abalone have not been pushed to deep waters by human predation.

Competition is an alternate explanation for the upper limit of abalone distributions. In addition to Tutshulte's observations of interactions with pink abalone, there is weak evidence that white abalone may increase in abundance and move into shallower water when kelp forest cover is reduced (Owen et al., 1971). Tutschulte (1976, p 193) speculates that when the density of red abalone was reduced by fishing in the Coal Oil Point region near Santa Barbara in the 1960's, more white abalone were found at shallower depths (n=23 at depths of 6-12 m). The density of urchins increased in the same period, suggesting it was competition with abalone rather than urchins that confined the white abalone to deeper waters. In the northern part of the Mexican range (Zone I), white abalone were found in the same habitat as red abalone but had non-overlapping vertical distributions (Guzman del Proo, 1992, p. 342, 345). These pieces of evidence suggest that the upper depth limit of white abalone may be due to congeneric competition.

Competition between abalone and urchins has been documented in other countries. Shepherd (1973b) found the urchin Centrostephanus rodgersii and the Australian abalone H. rubra had non-overlapping vertical distributions where the urchin was common, but that the vertical distribution was continuous where the urchin was rare (exposed habitats with few crevices). More experiments are needed to test hypotheses about limits or changes in abalone depth ranges due to competition or predation.

The vertical limits of abalone distributions may also be controlled by temperature (Leighton, 1974). Three of the California species (H. walallensis, H. rufescens, and H. kamtschatkana) submerge in the southern portion of the range, where water temperature increases (Lindberg, 1992, p IO). The lower limits of abalone distributions are affected by temperature influences on larvae and juveniles (Leighton, 1974). White abalone larval survival is reduced at low temperatures (Leighton, 1972), and this may set the lower distribution limit for this species. In addition, adult transplants of two shallow-living California abalone species to deep-water resulted in reduced growth (Tutschulte, 1976). The abundance of their brown algal food supply becomes limited at greater depths and may also affect the lower limit for white abalone (Davis et al., 1998).

Abalone may change their depth distribution with age, however, there is no evidence for ontogenetic migration in white abalone. This pattern is known conclusively for only one abalone species, the Australian intertidal species H. roei, which moves deeper with age (Wells and Keesing, 1990). It appears that H. kamtschatkana may also have an ontogenetic migration, but the reverse pattern occurs, with settlement in deep water and movement to shallow water with age (Breen, 1986). In northern California red abalone may undergo an ontogenctic migration (Karpov et al., 1998). In all these cases, the alternative hypothesis that there is differential settlement or survival with depth was not eliminated.

4.1 .8. Density.

White abalone density will be discussed in detail in a subsequent section, but a few points are relevant here. White abalone were considered rare when first described (Bartsch, 1940); however, confusion with other species and the deep range may have led to this conclusion. In September 1939 only four animals were found after a “diligent search for two weeks” (Bartsch, 1940).

The earliest fishery-independent white abalone density estimates are from the period 1969- 1972. White abalone density in California in the 1970’s is often quoted as about 1 m^{-2} (Davis et al., 1996, Haaker, 1998). This figure seems to be a “best guess” by Tutschulte (1976), apparently based on his previous experience as a commercial fisherman. In fact, the data in Tutschulte (1976, p257, Appendix Table 4a) came from a total of only seven animals in three quadrats (each of area 10 m^2) at depths of 20 m (4 abalone), 20 m (0 abalone), and 33 m (3 abalone) in 197 I. This corresponds to a density of 0.23 abalone m^{-2}. In an attempt to look at distances between nearest neighbors, he found three white abalone in a 7 m x 5 m quadrat at 20 m depth in the Isthrnus region of Santa Catalina Island in 1967, which corresponds to a density of 0.0857 abalone m^{-2}. This quadrat was intentionally located in an area of high pink abalone density (0.6 m^{-2}). These four quadrats constitute the only white abalone density data in Tutschulte (1976), and are also used to support his contention that white abalone increase in abundance with depth.

Guzman del Proo et al. (1976) calculated white abalone densities of between 0 and 0.4 16 m^{-2} during 1968-1970 transect and quadrat surveys off Baja California, based on a total of 35 individuals observed. Since then, white abalone densities have declined by several orders of magnitude (Table 2). (See also sections 6.2 and 7.2).

4.1.9. Sex ratio.

The sex ratio of 600 legal size white abalone collected over a period of several years at the Channel Islands was 1: I over all size classes; however, more males were recorded at larger sizes (Tutschulte, 1976; Tutschulte and Connell, 198 I). A size-skewed sex ratio is common among invertebrates where growth and reproduction are considered to be competing energetic processes (Wenner, 1972). In molluscs, it is usually the females that dominate the larger size classes, while in crustaceans it is the males (Wenner, 1972). Green and pink abalone harvested in Mexico in 1973 had. a female-skewed sex ratio among mature animals (Qunitanilla and Aceves, 1976).

4.1. IO. Sexual maturity.

White abalone reach sexual maturity in about 4-6 years, at a size between 88 and 134 mm (Tutschulte and Connell, 198 I). This compares with 5-7 years for green abalone (females 6 1 - 128 mm, males 89-128 mm), and 3-4 years in pink abalone (about 35 mm) (Tutschulte and Connell, 1981).

Latitudinal variation in age or size of maturity has not been examined in white abalone. The size of sexual maturity (50% of animals with mature gonads) decreases from north to south for red and black abalone in Mexico, and has led to different minimum size limits for different areas (Table 3) (Guzman del Proo, 1992). The legal minimum size for white abalone harvest decreases from north to south in Mexico, which may be a reflection of different sizes at which maturity is reached; however, we have not found data supporting this management strategy.

4. I. I 1. Movement.

Juvenile abalone of all species may move tens of meters, but this tendency decreases with age (Cox, 1962, Tutschulte, 1976). Adult abalone generally have very limited movements and become less cryptic with increasing size (Shepherd, 1973: Tutschulte, 1976, p 267).

Large white abalone are emergent, found on the tops and sides of rocky substrates; they are not as cryptic as other California abalone species (Tutschulte, 1976, p 267). In field tagging experiments, mature white abalone were more sedentary than adult pink or green abalone (Tutschulte, 1976, p 22 1). This sedentary lifestyle makes repopulating depleted ureas via migration unlikely.

4.2. Kcproduction.

The interaction between density, spawning period and length, and fecundity has been implicated in the success of abalone recruitment (Shepherd, 1986; Tegner, 1993; Karpov et al., 1998). The importance of maintaining spawning densities for effective stock management has only recently been appreciated:

> The more we take, the more they make
> In deep sea matrimony
> Race suicide can not betide
> The fertile abalone (Carmel Fisherman, 19 13, Lundy 1997, p 3 1).

4.2. I. Fecundity.

The number of eggs and sperm produced is the first factor influencing the potential number of offspring.. A linear relationship between egg number and animal weight, or a power relationship between egg number and shell length, has been shown in all abalone species examined. The complete relationship between fecundity and size has not been documented for white abalone; however, in all other species studied, fecundity increases linearly or allometrically with body size (e.g. H. kamtschatkana and H. tuberculata) (Tutschulte, 1976; Clavier, 1992; Campbell et al, unpublished report investigating the reopening of British Columbia fishery).

White abalone have the highest fecundity among the California green, pink, and white abalone, as measured from gonad volume and oocyte density (Tutschulte, 1976; Tutschulte and Connell, 198 I). White abalone females from 27-33 m at Santa Catalina Island had estimated fecundities (gonad volume x egg density) of 3.69-6.53 x 10^6 eggs (Tutschulte arid Connell, 1981).

Variation in fecundity with depth, region, or among years has not been documented for white abalone, but is often related to food supply in other abalone species. Fecundity was lower in H. laevigata transplanted to sites with less food (Shepherd et al., 1992). Abalone living in deeper water may have reduced fecundity if they are food limited, and one deep population of pink abalone did not appear to spawn in one year (Tutschulte, 1976, p 40). Cox (1962) reported that abalone gonads did not increase in size during 1957, 1958, and 1959 when an unusual influx of warm water destroyed kelp forests. In 1983 (during a strong El Nino event), a shallow population of food- limited green abalone also had minimal reproductive output (Tegner and Dayton, 1987, p262).

4.2.2. Spawning period and length.

The length of the spawning season can also influence reproductive success. White abalone are winter spawners, with one gametic cycle per year, and have a high degree of spawning synchronicity compared with two other California species (Tutschulte and Connell, 198 1). It is not clear if this synchronicity has an environmental cue, such as temperature. A cue is important in ensuring that sperm and eggs are released at the same time, or else fertilization cannot result. The release of sperm triggers the release of eggs in some species (Cox., 1962).

White abalone at a depth of 30 m spawned February to April, during a time of rapid temperature change; however, a shallower population at the same location (18 m) was not exposed to the same temperature changes and still spawned in February and March (Tutschulte 1976). Most of the other California abalone species spawn during spring and summer (Cox, 1960, Owen et al., 1971). Green abalone have been found to be summer spawners (between July and August) (Tutschulte and Connell, 198 1), or to have spring and fall spawning peaks (Tegner and Dayton, 1987). Pink abalone have less synchronicity within local populations and may be continuous or mixed spawners (Tutschulte and Connell, 198 1).

The duration of individual spawning events is unknown in white abalone, but in H. tuberculata spawning time was 40-80 minutes (Clavier, 1992). Sperm were released every 30-45 seconds in 30-70 pulses, depending on shell length. Males released 2-3x 10^9 sperm cells every pulse (Clavier, 1992).

4.2.3. Spawning density.

Successful fertilization for broadcast spawners requires that animals be close enough for the free-swimming sperm to contact eggs in sufficient densities. Although this concept is now accepted, it was only recently demonstrated (Pennington, 1985). The information on densities required for successful fertilization comes from models, artificial experiments, or urchin spawning (Pennington, 1985; Levitan et al., 1992; Levitan, 1995; Levitan and Sewell, 1998). There is no information for white abalone and very little field data for any abalone species (but see Babcock and Keesing, 1999).

Aggregation through movement is one way to increase the local density at the time of spawning, but this has not been documented for white abalone. Spawning aggregations have been reported for two abalone species. In H. laevigata spawning aggregations brought animals closer than one meter, although at low adult density this behavior was not observed (Shepherd, 1986). In H. kamtschatkana, animals formed piles for spawning (Breen and Adkins, 1980). An abalone aggregation has been defined as three or more large individuals (> l 10 mm) less than one meter apart (Shepherd and Brown, 1993). Shepherd and Brown (1993) found that the (density of aggregations declined as overall population density declined. At low overall densities, animals are not close enough for successful ferti t ization, and reproductive failure wit l occur.

4.2.4. Fertilization.

Variation in fertilization success has only recently been recognized in free-spawning marine invertebrates (reviewed by Levitan, 1995). Fertilization success is closely linked to the density of the spawning animals. Much of this research was done using echinoids (e.g. Pennington, 1985; Levitan et al., 1992). Pennington (1985) demonstrated for the first time that the fertilization success of broadcast-spawning animals was not always high, and was influenced by the proximity of spawning adut ts. At low densities, fertilization success was often much reduced. and at great separations, negligible.

Abalone fertilization success is related to the concentration of sperm and eggs. In H. tuberculata fertilization success was very low or zero when sperm concentration was less than 1000 cells/ml, and was optimal at 10^5- 10" cells/ml (Clavier, 1992). When male H. laevigata were only two meters upstream of females, fertilization success in the field was 48% (Babcock and Keesing, 1999). At a distance of eight meters., success fell to just over 20%, while at 16 m separation, fertilization success was less than 5%. Babcock and Keesing (1999) concluded that a drop in fertilization success below 50% in H. laevigata would come when the density of spawning animals fell below 0.15 m^{-2}, conclusions which are supported by fisheries data. Once commercially viable populations of this species suffered recruitment collapse after being fished down to densities of 0.15-0.3 m^{-2}, corresponding to nearest neighbor distances of one to two meters.

There are no field studies of fertilization success in white abalone, and only a single laboratory study in which fertilization success of about 5% was found (Leighton, 1972:). This may be poor relative: to natural spawning, as induced spawning in the laboratory often results in tower fertilization success (Levitan, 1995). Fertilized white abalone eggs are about 190-200 microns in diameter and sink (Leighton, 1972).

4.3. Settlement, recruitment and growth.

4.3.1. Settlement.

Settlement of white abalone larvae following induced spawning in the laboratory occurred after nine to ten days at 15°C (Leighton, 1972). This is a longer larval period than for other California abalone for which data are available (red and green abalone larvae settle in as little as four days, pink abalone settle after nine days; larval development rate is temperature dcpcndent) (Leighton, 1972). White abalone settlement rate was best at l 5- 16°C, and was not successful at 10-t 2°C (Leighton, t 972). Survival of larvae and growth of post-larvae was best at

18°C (Leighton, 1972). Temperature effects on larval survival have been implicated in establishing the lower and upper limits of the depth distribution for adult abalone (Leighton, 1974; Tutschulte, 1'976).

4.3.2. Larval dispersal distances.

No information exists on the distances that white abalone larvae disperse in the water column. Studies on several Australian abalone species have suggested very limited dispersal distances (Prince et al., 198'7; McShane et al., 1988). Tegner and Butler (1985b) used drift tubes to infer dispersal distances for green abalone: in California, and found that larval lifetime was not usually long enough for regular connections between island and mainland populations. These inferences were supported by recruitment from an experimental brood stock transplant of green abalone (Tegner, 1992). Given the apparently longer larval lifetime of white abalone., greater dispersal distances may be possible, and links between island and mainland populations may occur more regularly.

Restricted dispersal distances are an advantage if the adult habitat is also suitable for the juveniles, as in abalone. On the other hand, limited dispersal means the recolonization of a depleted habitat will be poor. Three of the five recognized west coast abalone subspecies are found at Guadeloupe Island, Mexico, which is further evidence for limited larval dispersal between isolated locations for these abalone species.

4.3.3. Recruitment.

Generally abalone are cryptic until they reach about 75- 100 mm in length at an age of 3-5 years (Cox, 1962), occupying habitats such as the undersides of rocks and deep crevices. Above this size they emerge from these habitats, and are more easily visible. Animals that are visible without disturbing the habitat are classed as emergent in diving surveys.

Recruitment is defined here as the number of white abalone growing to emergent size that are detected in non,-destructive field surveys. This size is still below the legal minimum for capture. No direct measurements of cryptic white abalone densities have been made. According to Tutschulte (1976, p3 I), white abalone smaller than 130 mm were rare even in a relatively undisturbed area prior to the peak of the white abalone fishery (Ship Rock, Catalina Island in 197 I). This suggests either that recruitment is a rare event or that cryptic animals arc extremely difficult to find. Tutschulte (1976, p 234) made a single collection of emergent white abalone where size was measured in 197 l (n=34). These data were subjected to polymodal analysis to determine age structure of the collection (Tutshulte, 1976, p. 230). He observed a peak of five year old animals (Tutschulte, 1976, p 277), suggesting that there was successful recruitment in 1966, and poor recruitment in the following years. This observation has been used as evidence that white abalone have irregular recruitment. More recent field surveys have also failed to detect juvenile white abalone (Davis et al., 1996).

There is no information about other possible influences on white abalone recruitment, such as water temperature or food supply. Recruitment of other abalone species also appears to vary dramatically in space and time, both in fished and unfished populations (e.g. Breen, 1986;

Karpov et al., 1998). Declines in abalone settlement and recruitment, and hence future population size, have been found in two cases where a fishery was not responsible (f-i. iris in New Zealand, and H. tuberculata in the English Channel) (Brcen 1986, p 308). In these cases, natural environmental factors were implicated, and the conclusion was drawn that abalone have innately variable recruitment.

4.3.4. Growth rate.

There is limited information on growth rates of white abalone. At 130 days after settlement in the laboratory, the average size of white abalone was 5.5 mm ± 1 .O 1 mm (or 15.4 mm yr^{-1}) (Leighton, 1972). Animals held in the laboratory and fed on Macrocystis had growth rates of 16.4 ± 7.8 mm yr^{-1} for adults (> 100 mm length, n=3), and 29.2 ± 15.0 mm yr^{-1} for juveniles, (<100 mm length, n=5) (Tutschulte, 1976, p62). In the laboratory, white abalone ‘growth was higher in, winter (although the water temperature was not reported) (Tutschulte and Connell, 198X).

No mark-recapture studies for natural populations of white abalone have been conducted. A single adult held in a cage at a depth of nine meters grew 12 mm in one year (Tutschulte, 1976, p 120). Size-of-year-class estimates from a sample of 20 animals collected over one year., produced estimates of growth rates of white abalone in natural populations of 23 mm yr^{-1} for the first five years and 10 mm yr^{-1} for the next three to four years (Tutschulte, 1976, p 103, Table 3.10). This estimate of 10 mm yr^{-1} for adult growth is not based on any data in the dissertation, and Tutschulte is inconsistent with the size categories used (compare table 3.1 1 with 3.3); however, this does not affect the results. Growth rates may be used to estimate the age of animals, but variation in growth can have a substantial effect on such estimates (Tutschulte, 1976).

4.3.5. Maximum&..

White abalone grow to a maximum size of 8-10 inches (20-25 cm) (Cox, 1960; Leighton, 1972), although a more average size is about S-8 inches (13-20 cm), and animals less than 4 inches (10 cm) arc rare (Cox, 1960). The type and paratype specimens were 2 18, 2 10 and 200 mm in length (Bartsch, 1940). Tutschulte (1976) assumed that the asymptotic size was 2 10 mm.

4.3.6. Estimated time to maximum size.

There are no direct measures of white abalone lifespan. Age may be inferred using size-age plots from mark--recapture studies or growth models. Using von Bertalannfy growth equations, with maximum size set at 210 mm, the time to grow to within l mm of maximum size was 34 years (Tutschulte and Conncll, 1988), or using the same data, 35 years (Tutschulte, 1976, p 107). The maximum lifespan of white abalone was estimated at 35-40 years (Tutschultt:, 1976).

Abalone age has been determined for some species from shell growth rings (e.g. Shepherd et al ., 1995; Shepherd and Avalos-Borja, 1997; Shepherd and Turrubiates-Morales, 1997). These methods arc generally difficult, and somewhat inaccurate. Size and age are not always well related due to differencc.4 in growth rates attributed to varying biotic and abiotic conditions. There have been no attempts to age white abalone from shell growth rings.

3.3.7. Mortality.

Mortality is comprised of natural mortality for unfished populations, or total mortality (natural plus fishing mortality) for exploited populations. Natural mortality may vary with age, location, and time, and generally declines with age for abalone (Tegner and Butler, 198.5; Prince et al., 1988; Shepherd and Daume, 1996). Natural mortality can be due to starvation, disease, old age, predation, as well as a variety of abiotic factors (Shepherd and Breen., 1992). Abalone larval mortality is assumed to be high, and survival to settlement was around 5% in laboratory studies (Leighton, 1972). No field estimates of larval, juvenile, or adult white abalone mortality have been reported. In laboratory observations, mortality of adult white abalone occurred when the water temperature exceeded 19°C (Lafferty, unpublished data). Tutschulte (1976, p 235) did not estimate total mortality for white abalone in the field (although he did for pink and green abalone).

Abiotic causes of mortality include factors such as storms, which lead to movement of rocks that may crush abalone (Tegner, 1989). Storms are unlikely to affect the deep-living white abalone and in fact may even provide more drift algae as food for short periods. In shallow waters, suspension of sediments may foul the gills of some abalone, leading to “suffocation” (Cox, 1962, Shepherd and Breen 1992). Disease that may cause white abalone mortality is discussed in section 9.7.

5. Abalone harvest, sale and preparation.

Abalone have been harvested by a variety of methods over the last century, including shore picking, free diving, hard-hat diving, hookah, and scuba diving. Recent harvest techniques in southern California in the range of the white abalone were scuba (recreational) or hookah (commercial) diving, using the only legal collection tool, an abalone iron. Fishermen insert this flat bar between the foot of the abalone and the rock to which it is attached, and pry the animal loose.

Once animals are collected, they are placed in a bag and returned to the boat. In California abalone must be landed in the shell to allow verification of species and size limits. Official receipts (pink tickets) must be issued by licensed seafood dealers when they purchase abalone from commercial fisherman (see section 6.2.2.1 for current restrictions). These receipts include the name of the fisherman, permit number and boat registration numbers, the numbers of each species received, and the block location or county where the abalone were collected (Tegner, 1989). Blocks are 0” 10’ squares, the data are summarized by the California Department of Fish and Game (CDFG) annually, and represent the source of most of the abundance information for abalone. The recreational fishery is only partially monitored. Commercial Passenger Fishing Vessels (CPFV) are required to record all fish taken, but do not always identify abalone to species. Individual divers and boat operators are occasionally surveyed in northern California, where only red abalone are harvested.

In Mexico abalone are harvested by commercial divers only, using hookah or shore picking (Leon and Muncino, 1996). Only recently have abalone been landed in the shell, which allows greater enforcement of' species-specific size limits. Species identification of harvested abalones is less rigorous in the Mexican fishery, and often only the amount of processed meat is reported. Sporadic monitoring of the catch is undertaken by the local fishermen, by the Instituto Nacional de la Pesca, and the Centro Regional de Investigacion Pesquera.

Processing of the catch occurs on land. Preparation for sale has included drying (Edwards, 19 13a), canning (Bonnot, 1930), and butchering of fresh steaks (Edwards, 19 13a). Historically most abalone were exported to China and Japan; more recently all production (with the exception of black abalone) was consumed in California. Demand for abalone in California exceeded the catch prior to closure in 1997, and 78% of the demand was satisfied via imports from Mexico (Tegner, 1989). With California commercial fisheries now closed, all demand must be satisfied by imports, which come mostly from Mexico, and from cultured animals. White abalone have not been cultured.

Fishing effort., as discussed in this report, is a function of direct fisherman participation and fishing time. Effort may be influenced by equipment, weather, economics, availability of abalone, and regulations.

6. California white abalone.

6.1. Exploitation history of California abalone.

Five abalone species, the black, red, green, pink and white abalones, have been commercially fished in California at some time over the past 1 SO years (Haaker, 1994). Management was based on minimum size limits and a closed season during spawning; however, this was inadequate to protect stocks of sufficient density for successful reproduction (Davis et al., 1998). Recent declines in the catch of all California abalone species have been well documented (e.g. Davis et al., 1992; Tegner, 1993; Altstatt et al., 1996).

Because the abalone fishery targeted more than one species, the history of exploitation of white abalone cannot be considered in isolation. A complete history of the abalone fishery prior to 1960 is given by Cox (1962), and a popular account by Lundy (1997). The exploitation history is summarized below.

Native Americans began harvesting abalone for food and shells about 7000 BC (Croker, 193 I). Abalone, or "uhllo" shells were used as currency, and when horses were first introduced by the Spanish, one abalone shell was worth a single horse (Croker, 193 1, p60). Native Americans probably did not collect the deeper living white abalone, as no shells have been recovered in the middens on Santa Rosa Island (Cox, 1962). Native harvest was halted when the Catholic church removed Native Americans from the Channel Islands in the early 1800's (see Davis et al., 1992). 'This removal coincided with the local extinction of sea otters from hunting, and both have been implicated in allowing abalone to reach commercially harvestable densities (Cox, 1962; Tegner, 1989).

The modern abalone fishery was initiated by Chinese immigrants in the 1850's, and in southern California mainly involved hand gathering of the intertidal black: abalone, and the use of rowboats and gaffing hooks to collect subtidal green abalone. These species were dried and exported to China (Lundy, 1997, p 5). In 1853 some harvesting of red abalone occurred in Monterey by a community of 500-600 Chinese (Lundy, 1997, p 5). The shell was worth almost as much as the meat at this time, and was used in local and Chinese crafts andjewelry (Lundy, 1997, p 9). Red abalone sold for between 12 and 20 cents/lb dry weight in 1856 (Lundy, 1997, p 6). By 1879 the harvest of green and black abalone was estimated at 1700 tons. The price of meat was usually about 5 cents/lb. The gross earnings from shells exceeded the gross income from meat (Croker, 193 1, p61). In 1895 the price of meat was about 4.5 cents/lb (Lundy, 1997, p10). A Mr. Sorenson (in a 1939 communication to Bartsch, 1940) claimed to be familiar with the industry/and or the coast of California from 1885 onwards. Prior to 1940 #Sorenson claimed little harvest took place south of Point Conception, but that some boats did go as far as Santa Barbara. Most abalone were landed in the Monterey region.

In 1888 California legislation made it illegal for Chinese fishermen to leave and reenter the United States. This effectively ended the movement of Chinese between Mexico and San Diego, and may have reduced abalone imports from Mexico (Lundy, 1997, p1 1). The Chinese fishery was virtually eliminated in 1900, when shore-gathering was prohibited in many southern California counties due to "concern" for low numbers (Bonnot, 1930).

In 1909 regulations allowing the harvesting of red abalone only were established. However, this law was repealed in 19 1 1, when possession of all abalone species was allowed. The first commercial abalone landing data were gathered by the California Department of Fish and Game (CDFG) en 1916, marking the beginning of monitoring of the abalone fishery.

Japanese immigrants to California were the major participants in the fishery between 1898 and 194 1. They began hard-hat diving for subtidal abalone species about 1900 (Bonnot, 1930; Cox, 1962). Air was pumped from the surface to divers who worked primarily at depths between 20 and 50 feet; their maximum depth was about 100 feet because air could not be pumped deeper by the available equipment (Bonnot, 1930; Croker, 193 1 p 64; Lundy, 1997, p 30). Between 1898 and 1915 the Japanese harvest was dried for export to Asian markets. In 1913-1915, however, the export and drying of abalone was prohibited (Croker, 1931, p 62), and abalone steaks became the product of choice for sale to California restaurants (Bonnot, 1930; Lundy, 1997). From 19 16- 1929 almost the entire catch of about 2 million pounds per year was taken by Japanese fishermen and landed at Monterey (Cox, 1962, p 84). The Japanese fleet was comprised of about 16 mother boats, each with one or more small collecting boats (Lundy, 1997, p32). The price of abalone was about $2/dozen in 1930, or 5 cents/lb of meat (Croker, 193 1, p 65). Shore harvest by recreational fisherman was also underway in some regions at about this time.

According to 1933 CDFG regulations, only red, pink, black, and green abalone were legal for commercial and recreational harvest. Most harvest was north of Point Conception., so white abalone were: probably not harvested in significant numbers. White abalone were known by Mexican fisherman to occur in deeper waters, and their fine tender flesh attracted the highest price (Croker, 193 1, p 69).

In 1939 four white abalone were found in two weeks of searching southeast of Point Conception on the Santa Barbara Breakwater at a depth of about 20 m (Bartsch, 1940, p 50). The species was described scientifically the following year (Bartsch, 1940).

In 1941 Japanese immigrants were moved to World War II internrnent camps which effectively allowed Caucasian fishermen to completely take over the California abalone fishery. The mainland coast south of Point Conception was reopened and the Channel Islands opened to commercial abalone fishing in 1943 (Tegner, 1989). This was apparently due to a need for food during the war years (Lundy, 1997, p100). Harvest of green and pink abalone occurred in these regions. A limited number of commercial divers occasionally harvested abalone south of Point Conception even before 1943 (Bartsch, 1940).

The coast north of Point Lobos, San Francisco County was permanently closed for commercial harvest of abalone in 1945. In 1952 the use of scuba to harvest abalone north of Yankee Point, Monterey County was also prohibited (Burge et al., 1975, 'Table 24; Lundy, 1997, p 138). While these restrictions had the effect of creating a good refuge area for northern species, this partial closure and protection from exploitation occurred north of the range of white abalone.

In 1955 white abalone was named as a species that could be harvested. Additional "refuges" from commercial fishing were created, including a ban on commercial harvesting of any abalone species within 150 feet of the shore, or in waters less than 20 feet deep (Lundy, 1997, p 138). Unfortunately, white abalone were not protected by these measures, as they did not occur in these areas.

The harvest of white abalone began in earnest in about 1968, at a time when the introduction of the Radon Boat, better diving equipment, improved fathometers, and the Loran navigation system allowed more isolated and deeper sites to be identified and harvested (Lundy, 1997). Increased harvest of white abalone also coincided with declines in the catch of the other abalone species. The peak of white abalone harvest occurred in 1973.

By 1978, the catch of white abalone had declined dramatically, and mandatory 'reporting of white abalone was eliminated because the animals became rare in the landings (Tegner, 1989). White abalone landed thereafter were either reported voluntarily, or included in a miscellaneous category (Davis et al., 1996). Unfortunately, dropping the reporting requirement may have prevented an earlier recognition of the seriousness of the decline in the abundance of this species.

In 1993 the harvest of black abalone was prohibited because of population declines attributed largely due to disease (Altstatt et al., 1996). This was followed in March 1996, by the closure of commercial and recreational harvest of-green, pink and white abalone in all of California. Red abalone could still be harvcstcd. Finally, in May 1997, all of California was closed to commercial abalone harvest and recreational harvest closed south of Point Lobos, San Francisco County, including the Farallon islands. Red abalone may still be harvested recreationally in northern California (Karpov et al., 1998). White abalone is currently the rarest of the west coast abalone species (Haaker, 1998).

6.2. Abundance patterns in California white abalone.

Abalone abundance and density patterns can be inferred from fishery-dependent data (recreational and commercial) and from fishery-independent surveys. These two data sources have been shown to be correlated for abalone stocks when a large area is surveyed (Karpov et al., 1998) and for underexploited populations with regular recruitment. Trends in the abundance and density of white abalone can thus be examined by considering both types of information.

6.2. 1. Fishery-independent data. California.

Fishery-independent data can be used to indicate latitudinal range., depth range and density. Prior to 1969, no surveys of white abalone density had been performed, and it was not until the 1980's that reliable estimates were made. Most abalone surveys count only emergent individuals, and so only provide an estimate of adult density. The difference between the density of adult (emergent) and juvenile (cryptic) abalone depends on the recruitment history (Karpov et al., 1998) and habitat structure. There is no way to estimate the number ofcryptic animals and obtain a total population density of white abalone.

The original scientific collection of white abalone was in 1939, when four animals were collected southcast of Point Conception, at a depth of about 10 fathoms (20 m) (Bartsch, 1940). The density or abundance of white abalone at this time was not determined. In 1959 five white abalone: were collected at depths of 15-30 feet (5-10 m) in the Palos Verdes area; again, however, there were no data on the size of the area surveyed (Owen et al., 197 1, p 33). Some counts of white abalone relative abundance were made by Owen et al. (197 1, p 3.3) between 1959 and 1966 from inspection of the commercial catch between Point Conception and La Jolla, at a variety of depths and habitats. The approximate location and number of each species is recorded, but not the area sampled.

The earliest fishery-independent white abalone density estimates are from the period 1969- 1972. Tutschulte (1976, p257, appendix Table 4a) found a total of seven white abalone in three quadrats (each of size 10 m^2) at depths of 20 (four abalone), 20 (zero abalone), and 33 m (three abalone) in 197 1. This corresponds to a density of 0.23 abalone m^{-2}. In an attempt to look at distances between nearest neighbors, he found three white abalone in a 7 m x 5 m quadrat at 20 m depth in the Isthmus region of Santa Catalina Island in 1967, corresponding to a density of 0.0857 abalone m^{-2}. This quadrat was located in an area of high abalone density (the same quadrat also had 2 1 pink abalone at a density of 0.6 m^{-2}). These four quadrats are the **only** density data presented for white abalone in Tutschulte (1976), and are also used to assert an increase in abundance with depth. The historical white abalone density of 1 m^{-2} is apparently a "best guess" of Tutschulte (1976). This figure has been widely used to estimate total population sizes; e.g., Davis et al. (1996) multiply that "best guess" to obtain a white abalone density of 10,000 ha^{-1} (1 ha^{-1} = 10,000 m^{-2}). This is an extremely large number, and in fact no abalone species appears to be at that density over such a large area. For example, the reported range of abalone densities in the 1970's (for reds, pinks and greens in southern California) range between 0.9-2.6 per 10 m^2 (dividing by 10 gives 0.09-0.26 abalone m^{-2}) (Davis et al., 1996). Some regions of northern California, however. have red abalone densities of 1 m^{-2} (Karpov et al., 1998).

The second set of fishery-independent white abalone surveys was undertaken in 1980-8 1. The Channel Islands National Park diving surveys covered the three eastern-most of the northern Channel Islands (Davis et al., 1996). These surveys were performed at 10 reefs, at depths of 24-30 m, and covered about 1000 m^2 at each reef. Emergent white abalone larger than 50 mm were likely to be detected in these searches. White abalone were found at all 10 sites (n=1-3 per site), but the total number of white abalone found was only 2 1. An average white abalone density of 0.002 1 m^{-2} (± SD 0.0009) was obtained by pooling all sites (Table 4). Since 1983, surveys of invertebrates at a number of Channel island kelp forests have been undertaken (Haaker, 1994). Most were at depths too shallow for white abalone, but if they are encountered their presence is noted **(Table** 5). It is apparent that white abalone were rarely encountered 'during those surveys.

In 1992 and 1993, National Park Service and CDFG divers conducted a third set of surveys to search for white abalone. These surveys covered 30,600 m^2 of suitable habitat at 15 locations at depths of 24-37 m (not 14 locations and 27,600 m^2 as in their table) (Davis et al., 1996; Davis pers. comm.) (Table 4). Some of the same regions surveyed in the 1980- 198 1 dive surveys were resurveyed, and some additional regions were included. Three live white abalone were found, the average density per site was 0.0002 white abalone m^{-2} ± SD 0.0005 **(not SE** as in Davis et al, 1996). The overall white abalone density was 0.000098 m^{-2} if all sites are pooled first **(Table** 4). This represents a tenfold decline in density in the ten years since the previous survey. A total of 1 19 white abalone shells was also found during the 1992/93 surveys and 97 of these shells were intact enough to be measured **(Figure 3).** All but one of the shells were adult size (>50 mm), indicating that successful recruitment had not occurred recently. The modal shell size of 141-150 mm is just before legal size (153 mm), and may represent both natural mortality and mortality of sub-legal animals accidentally cut during collection, and returned to the substrate. Consideration of the general pattern suggests that 20% of the pm-legal 14 1- 1 SO mm class mortality may be due to bar **cuts.** Larger legal-size abalone are landed in the shell, and so shells are not discarded on the fishing ground. Empty shells larger than 153 mm are likely to be the result of natural mortality. Compared to earlier surveys, dead shells also declined in abundance (Davis et al., 1996). The deterioration rate of dead abalone shells is unknown, but may take many years; the time since animals lived in the collected shells cannot be determined.

Following these diving surveys, more effort was made to search suitable white abalone habitat. The fourth and most recent set of surveys for white abalone was conducted by submersible at Osborn Bank and Anacapa, Santa Cruz, and Santa Barbara Islands in 1996-97. A total of 24 dives in the research submersible Delta covered 77, 050 m^2 of bottom at depths `` 30-**67** rn **(Table 6, Figure 4)** (Davis et al., 1998). Nine live white abalone were found between depths of 28-5 1 m (average 45 m). The density of live white abalone was 0.000 167 m^{-2}. (Davis et al, 1998). Over 300 dead white abalone shells were seen during these dives, which further supports the contention that appropriate habitat was surveyed. On Santa Cruz and Anacapa Islands suitable abalone habitat was restricted to a relatively narrow band less than 400 m wide above a depth of 50 m (**Table** 7). At Osborn Bank and Santa Barbara Island apparently suitable habitat extended to a depth of 67 rn. The depth to which suitable habitat extends on the other islands is not known (Davis et al., 1998). Davis et al. (1998) estimate that they are able to survey 10- 15% of the suitable habitat in a IO km stretch of coastline per day. At this rate, approximately 100 days of surveying would be required to statistically survey the complete historical range of white abalone. Because of limited ship time, these surveys have not been in the regions where the highest catches of white abalone were historically made (San Clemente island or Tanner and Cortez Banks); however, non-quantitative (but probably too shallow) surveys at these high historical catch locations have not detected white abalone **(Table 5).**

The densities of white abalone found in these four surveys show a decline of four orders of magnitude between **1972** and **1997 (Table 2).** This represents a greater than 99% reduction in density in the areas of southern California surveyed.

Several marine biological survey programs in southern California between 1966 and 1994, while not counting white abalone, did note the presence of white abalone if they were seen **(Table** 5) (Davis et al., 1996, Table 4.). These surveys were generally above the depths at which white abalone were historically common. The major result in terms of white abalone abundance from these survey programs is that few white abalone were observed in the late 1980's and early 1990's. San Clemente Island was included in some of these surveys, and no white abalone were observed.

In general, several findings should be emphasized. Juvenile white abalone shells have rarely been found, in contrast to other species where a wide range of shells are found (Tegner et al., 1989; Haaker, pers. comm.). Absence of juvenile white abalone shells suggests that white abalone recruitment has not occurred recently in the areas surveyed. Inferring lack of recruitment by the absence of juvenile shells is based on the assumption that juvenile shells decay at the same rate as those of adults. With thinner juvenile shells this assumption is unlikely to be true, however, large juvenile and small adult shells were also not observed. While a range of depths have not been quantitatively covered to truly determine the lower depth limit of white abalone in all portions of the range, or the change in abundance with depth, existing data indicate that white abalone are absent or at extremely low densities at all depths and areas surveyed so far.

6.2.2. Fishery-dependent data. California.

Fishery-dependent data can provide an index of abundance, but are limited by the fact that fishing effort may vary dramatically. Problems with fishery-dependent data for abalone are discussed by Haaker (1994). In this report the fishery-dependent data show a decline in catch, and by inference, in the abundance of white abalone.

6.2.2. I. Commercial fishery data

Prior to 19 15, when CDFG monitoring began, the catch (weight in shell) of all abalone species was substantial, over 4.1 million pounds in 1879 (Cox, 1962, p 76). Commercial catch data for all abalone species in California are available from **19** 15- **1997 (Figure 5).** The harvest increased until 1935, then there was a drop during the second world war, before the catch again rose. In 1947 about 35-40 diving permits were issued free to commercial operators (Lundy, 1997, p 107). By the early 1950's the fleet size had grown to about 75 boats. Hard-hat divers harvested over 4 million pounds, averaging 52,000 to 67,000 pounds per boat per year. (Burge et al., 1975, p 2, 6). The harvest was relatively constant from about 1950- 1967, peaking at five million pounds in 19.57. By 1974 the commercial fleet size included over 2 10 boats and 360 divers **(Figure** 6) (Burge et al, 19'75, p 2. 6). This increase in effort saw many novice divers enter the fishery. Novice fisherman pick a higher proportion of sub-legal abalone compared with experienced fishermen, causing bar-cuts and deaths (Burge et al., 1975, p 6). The number of divers fell to about 150 in 1979. then declined slowly to about 100 in 1990 **(Figure 6).** The decline in total abalone landings began in 1968, fell to one million pounds by 1980, and was less than 120,000 pounds when the commercial fishery closed in 1997 **(Figure 5).**

The pattern in abalone landings reflects three main trends, a southward shift in the tishing grounds, changes in species composition **(Figure 7)**, and decline in all landings beginning in about 1968 **(Figure 5)** (Tegner. 1989, p 403). As red abalone declined, fishing effort shifted from red to pink to green to white to black and back to red abalone. These data indicate that rota! abalone landings did not decline in the initial 20 years of the fishery because of serial 'depletion as fishermen moved from exploited to unexploited species and areas (also Tegner et al ., 1992). For example black abalone, used only as lobster bait prior to 1969, was then allowed to be dried and exported, which increased effort for this species (Lundy **1997,** p **167) (Figure 7).** Obviously the practice of harvesting unexploited regions only worked for a short time, as eventually all areas were exploited and region-wide decline in each abalone species occurred.

The red abalone was the dominant species harvested, comprising over 63% of total California landings between **1915** and **1997** **(Figure** 8). Pink abalone ranked second in importance, while black and green were taken in smaller quantities. White abalone was the least important species, comprising about 0.3% of the total commercial harvest. Only 0.02% of harvested abalone were not identified to species in the landings.

Commercial white abalone harvest began in 1967 when the total abalone catch began to decline **(Figure 7).** Over 95% of the commercial white abalone landings took place in nine years, between 1969- 1977 **(Figure 9).** The peak catch of white abalone of 144,000 pounds (86,000 individuals) came in 1972, only three years after intense harvest of this species began. In 1978 the white abalone catch declined dramatically. The decline was such that, separate reporting of the white abalone catch on CDFC "pink tickets" was no longer required (Tcgner, 1989). Because of this, conservative estimates of white abalone abundance from catch data have sometimes combined the white abalone with the miscellaneous catch after 1978 (Davis et al., 1996). This treatment of the data does not influence the pattern, as the miscellaneous catch is small, and the other commercial species still had to be identified. The voluntarily reported white abalone harvest was less than 1000 pounds per year after 1978. Between 1987- 1992 only 1 1 white abalone were reported in commercial landings, and since 1992 none have been reported. White abalone were harvested 10 months of the year, with February and August closed to harvest **(Figure 10).** These closures were the same for all abalone species, and were ostensibly implemented to offer some protection to spawning animals. The declines in landings show that these closures were not sufficient to maintain harvestable densities.

White abalone annual catch data were recorded by block location (0" t 0' squares) for the period 1955-1995. In turn these blocks can be ggregated into regions (**Table** 8; **Figure 1 1**). Over 80% of the total white abalone catch came from a single region, San Clemente Island. A second region, the offshore 'Tanner Bank and Cortes Bank-Bishop Rock, provided 13% of the catch. while the remaining I t regions, including three regions along the mainland of California, provided less then 7% of landings. At each of the locations over a 25 year period, over 25%

(average 43%) of the catch came from a single year (**Table 8**). If harvest was sustainable, the portion of the catch taken in each year at each location should have been more equitable. At each location, large harvest was only sustained for a few years, and there was no evidence of new recruitment after virgin stocks were depleted. Consideration of these data indicate that large stocks of white abalone were limited to a few locations, that there was local depletion of accumulated biomass to extremely low numbers in each region, and that harvest of white abalone: was not sustainable.

The rapidly increasing value of abalone may have increased fishing pressure on a dwindling resource **(Figure 12).** The price of white abalone increased from about $2.50 per pound in 198 1 to about $7 per pound in 1993 **(Figure 12).** As catch declined, the total and per-unit value of the harvest continued to increase. The price varied with species and rose steadily **(Figure 13; Table** 9). White abalone was typically the most valuable species, and in 1987-88 was worth twice the value of the other species (Davis et al., 1996) **(Figure 13; Table 9).**

6.2.2.2. Recreational fishery data.

Recreational fishermen in California have also harvested a variety of abalone species over the last 50 years, including white abalone. Like the commercial data, recreational fishery-dependent data provide an index of abundance, rather than an accurate measure of population size.

The available recreational catch data for southern California comes from commercial passenger dive boats (CPDB's). CPDB's are a segrnent of the commercial passenger fishing vessel (CPFV) fleet that specializes in skin and scuba diving trips. CPDB's began serving recreational divers during the late 1940's (CEQA, 1997, section 3.3.1.3.3). The CDFG began monitoring log-books from CPDB's in 1958. Most of this CPDB activity occurs in southern California, as access to the offshore islands requires a boat, while along the northern and central coast of California, shore access to good diving locations is rnore readily available.

Most of the CPDB effort is concentrated at three of the northern Channel Islands. (Santa Rosa, Santa Cruz, and Anacapa), and three of the southern Channel Islands **(San** Clemente, Santa Catalina and Santa Barbara), with Santa Catalina Island attracting most attention (CEQA, 1997, p 3-63). Most trips are single day, but two-day or more trips are completed. Reporting by species harvested is voluntary, and problems with species identification or inflation of catch are concerns with these data. These data arc likely to overestimate effort, as not all divers will look for abalone, especially in closed seasons, or when other target animals (e.g. spiny lobster) are available.

The catch by CPDB fishermen increased from 1960 until about 1972, then declined **(Figure 14A).** Diver effort, as measured by number of diver days, increased from 1960, reached a peak in 1973, and then declined until 1984, before increasing again in the late 1980's **(Figure 14A).** The recreational diver catch per unit effort for all abalone species has declined since monitoring began **(Figure 14B).** The decline in recreational catch has been similar in all species, although identification of the catch was only initiated in 197 I **(Figure 15).** In response to perceived reductions in abalone abundance, the CPDB-industry sponsored a reduction in the recreational catch (four abalone to two abalone per day), and the length of season (ten-month to seven-month) south of Yankee Point, Monterey County, in 1989 (CEQA, 3-59). This reduction in catch limit corresponded with a steep decline in diver days between 1989 and 1990 **(Figure 14A)**, and with a dccilinc in the landings of most species **(Figure 15)**, but not in the reported landings of white abalone which were already at **low levels (Figure 14A).** 'While the decline in landings may have been influenced by the reduction of the catch limit, a decline in the landings due to low abundance of legal-sized abalone of all species is strongly supported by fishery--independent data.

A total of 570,930 abalone of five species (45% of the catch) and unidentified species (55% of the catch) were reportedly harvested from CPDB's between 197 I and 1993 in southern California **(Figure** 16). Green abalone were the most important species harvested by recreational divers, followed by pink and red abalone. White abalone comprised 1.29% of the total and 2.89 % of the identified recreational catch in that period. Some of the unidentified abalone were probably white abalone. If the unidentified catch represents lazy reporting, then the unidentified catch might be allocated to each species in the proportion as the identified 'species. The number of white abalone harvested recreationally peaked in 1975, at about 35,000 animals, then declined sharply. By 1986, white abalone were rarely taken **(Figure 14A).** Most of the white abalone were harvested from Santa Catalina and San Clemente Islands, and to a lesser extent from Santa Cruz and Anacapa Islands (CEQA 3-64).

In the same period (1971-1993), the total reported commercial catch of all species was 1 1,998,63 1 abalone (assuming that the average abalone weighed 2.5 pounds, see Pinkas, 1974). Thus, the reported CPDB recreational catch in southern California was about 5% of the commercial catch (also from southern California).

The abalone catch from non-CPDB recreational divers has not been quantified. Given that the catch rate on the CPDB trips was about 1.3 abalone per diver per day, if the number of non-CPFB divers and the number of abalone trips they made was known, an estimate could be attempted. The number of active certified scuba divers in California was recently estimated at 200,000 to 250,000 individuals. about 10% of the state's estimated 2,000,000 certified divers. The fraction of these that use CPFB's or harvest abalone is unknown.

In surveys of the fish and invertebrate harvest by private boat operators between 1980 and 1983, white abalone was not recorded because of very low abundance (CEQA, Table 3-8). There have been no subsequent surveys of recreational abalone catch in southern California.

6.3. History of management regulations. California.

6.3.1. Minimum size limits.

Minimum sizes have historically been used worldwide to safeguard abalone resources from overfishing. Size limits that allow individuals a number of years of' reproduction before they enter the fishery were believed to be central to a prudent management strategy. The first abalone law created in 190 I established a minimum size for the harvesting of abalone. That law stated that all collected abalone had to be greater than 15 inches in circumference (approx. 4.75

inches in diameter) (Cox, 1962). In 19 17 identical minimum sizes were established for red, green, pink, and black abalone for both the commercial and sport fishery (Cox, 1962) (15" circumference (i.e. 4.75" (120 mm) diameter). Changes in the size limit of one species may have led to increased or decreased effort on another species. For example, the size limit for pink abalone was increased in 1970 to 159 mm, which led to a drop in pink abalone landings, and may have increased harvest pressure on the less exploited white abalone, even though its minimum size limit was also increased to the same size **(Figure 7).**

Size limits for California species prior to closure of the fishery (Table 3) were all greater than the size of sexual maturity and allowed several years of additional growth before animals reached legal size. This should have allowed several years of reproduction before these animals were harvested; however, successful reproduction does not occur every year. Reproductive failure may be caused by a variety of poorly understood environmental factors that act on all stages of the reproductive process. If reproductive failure occurs for several years, abalone may grow from the size of maturity to the harvestable size, and be removed by the fishery without making a reproductive contribution. For this reason, size limits may fail if used as the primary management tool in an abalone fishery, in the absence of adequate fishery-independent data.

6.3.2. Commercial permit fee.

Prior to 1909 there was no fee to commercially harvest abalone. In 1909, a commercial license for citizens cost $2.50, while for aliens, who were the major operators in the fishery, it cost $ 10. Legislators made the cost $10 for all licenses in 19 13. In 1970 the fee for an abalone permit was set at $100 for both divers and crew members (Burge et al., 1975, p 22). The divers fee increased to $200 in 1975, while the crew member fee remained at $100 until it was dropped in 1987 (Burge et al., 1975, p 6). In 1986 the diver fee increased again, to $250, then in 1991 went to $330 and the crew member fee was reintroduced at $33 (Lundy, 1997, p213). These fees are too low to encourage good stewardship of the resource, compared with other regions of the world where license fees may approach one million dollars (Tasmania, South Australia) (Prince and Shepherd, 1992).

6.3.3. Minimum commercial landings.

When landings began to decline in the 1970's, attempts were made to reduce effort in the fishery via reduction in the number of participating divers. The first restriction, implemented in 1976, was that the permit holder must land 10,000 pounds or make 20 landings to hold the license for next year. Because many full-tirne abalone fisherman had trouble making this level, the annual requirernent was decreased to 6,000 pounds or 20 landings of 24 abalone each in 1979. Even with these changes, the commercial catch continued to decline, and in 1990 the annual requirement was reduced to a minimum landing of 1,200 pounds, or 320 abalone per year (Lundy, 1997).

63.4. Recreational limits (southern California).

A variety of regulations in addition to size limits were also applied to recreational fishermen in California. To enforce size limits, all abalone had to be landed alive and in the shell from 191 1 onwards. The first bag limit of ten abalone per day was imposed in I9 13 (Cox, 1962). As knowledge of incidental mortality of sub legal animals increased, additional measures were imposed. A 1939 regulation stipulated that all undersized abalone must be replaced immediately to the rock from which they were removed. The catch limit was decreased to four abalone of any species per day in 1976. In addition, all legal-sized animals detached must be retained, until the catch limit was obtained. The limit was decreased to two per day south of 'Yankee Point in 1989 as catches declined further.

6.3.5. Recreational and commercial gear regulations.

Diving gear was prohibited for collection of abalone in 1907, but this regulation was abandoned in 1909. In 1913 the first law regulating recreational collecting methodology banned the spearing of subtidal abalone from the surface, a harvest technique used by Japanese fishermen (Lundy 1997). Between 19 13 and 1957 there were various openings and closings of regions for abalone harvest. After 1939 a measuring gauge had to be carried by all divers, to allow the identification of legal animals before they were brought to the surface.

The use of' scuba to collect abalone was prohibited in 1952, although in 1953 this regulation was amended to allow recreational scuba south of Yankee Point, Monterey County. Commercial harvesters were required to use surface--supplied air through a 100 foot hose (hookah) in 1954. In 1974, abalone irons of specific dimensions were established as the only tool to be used for collection of abalone by both recreational and commercial fishermen.

In addition to these regulations, commercial harvesters may only collect abalone when they are targeted. Thus, if a diver is on an urchin-harvesting trip, encountered abalone may not be taken. The large areas searched for sea urchins in combination with the technological advance afforded by Global Positioning System (GPS), however, increased the pressure on dwindling abalone stocks by allowing divers to accurately mark abalone concentrations found while fishing urchins.

7. Mexican white abalone.

7.1. Exploitation history of Mexican abalone.

Five species have been commercially harvested along the west coast of Baja California (H. corrugata, H. fulgens, H. rufescens, H. sorenseni, and H. cracherodii) (Guzman del Proo, 1992). There is no recreational abalone fishery in Mexico, but probably some artisanal gathering of the intertidal species occurs. Deeper-living species (especially white abalone) are almost certainly restricted to commercial exploitation. 'The history of exploitation is generally sirnilar to that reported for California, and will be summarized briefly here.

As in California, Native Americans began harvesting abalone about 7000 BC. (Cox, 1962). After the 1860's Chinese and Japanese fishing took place on the same time frame as in California (Croker, 193 I; Cox, 1962). Maximum hard-hat diving depths were reported to be 15 fathoms (70 feet) (Crokcr, 193 l, p 7 I).

Foreign involvement in the fishery ceased when exclusive control of the Mexican abalone harvest was given to local villages by the Mexican government in 1945 (but may have been as early as 1936, Ramade-Villanueva et al., 1998). Originally the Pacific coast of Baja California between the Coronado Is. and Margarita Is. was divided into 19 cooperatives, which in turn were grouped into five larger zones for management (Guzman del Proo, 1992, Fig 24. I). The original Zone I and II of Guzman del Proo (1992) later merged to become the Zone 1 discussed in Leon and Muncino (1996). Accordingly, these adjustments are made to data from earlier periods where possible. The number of cooperatives has fluctuated over time. About 500 fisherman (180 divers) and 160 boats were involved in the fishery in 1987. Prior to 1992, the number of cooperatives harvesting abalone was about 14 (Table **10).** In 1992 the exclusive access to the abalone of Baja California by only the existing cooperatives was abandoned, and entry of additional fishing groups was allowed (i.e. new cooperatives), although this has not yet occurred (Ramade-Villanueva et al., 1998). As of 1996, a total of 22 cooperatives appeared poised to harvest abalone (Leon and Muncino, 1996). At that time some 200 fishing boats were targeting abalone (Leon and Muncino, 1996). The effect of the: increase in the number of cooperatives is unknown, as it is not clear whether the increase involves subdivision of existing cooperatives and their resources.

7.2. Abundance patterns in Mexican white abalone.

7.2.1. Fishery-independent data. Mexico.

The density and depth distributions of all abalone species were surveyed in 1968-70 along the west coast and islands of Baja California (Guzman del Proo et al., 1976). This elegant survey was designed to evaluate the status of the entire Mexican abalone resource. A total of 386 transects (or 306 in Guzman del Proo, 1992, describing the same data), was established running perpendicular to the shore. Transects ran from 0 to 27 m depth, were one mile wide and were subdivided at 2.5, 5, 7.5, 10, 12.5 and 15 fathoms into 24 blocks (thus each transect was 6 blocks long, 4 blocks wide). These depth divisions correspond to depth bins of O-4.5,4.5-9, 9-13.5, 13.5- 18, 18-22.5 and 22.5-27 m (1.8 m is one fathom, "brazas"). In each substratum, six quadrats (14.4 m^2) (or fve in Guzman del Proo, 1992, describing the same data) were randomly placed and all emergent abalone larger than 10 cm in diameter were recorded. A total of 232 1 quadrats was surveyed during the study. Smaller cryptic abalone and emergent juveniles were not surveyed. In the five zones, over the three years, a total of 546 abalone from all five Mexican species were found in quadrats frorn 80 of the 386 (or 306) transects. Ecological densities were calculated using only the transects in which abalone were observed. A total of 35 white abalone was found in this study (Table **11).** They occurred in Zones I-III (I-II of the later zone scheme). These were mostly between 15 and 27 m, although in 1969 a few white abalone were found at 10- 1.5 m` Using the total number and density of all species, and the size of quadrats, Guzman del Proo multiplied up to give density estimates per 1000 m^2, and plotted density as a function of depth. For white abalone these density distributions were occasionally based on only one or two animals. Densities of white abalone ranged between 0.07-o. 149 m^{-2} depending on the year and the zone (Table 2). In 1977-1978, zone III (zone II of the current scheme) was surveyed again, and no white abalone were found ('fable 2) (Guzman del Proo, 1992).

Unfortunately density estimates made in the 1980's for the other commercially harvested species did not include white abalone (Table 4 of Leon and Muncino, 1996). Thus, the only fishery independent data from the 1970's showed that white abalone were in similar densities to those found in California at the same time.

7.2.2. Fishery-dependent data. Mexico.

The Mexican data are less clear than those available for California. Identification to species prior to the enforcement of landing abalone in the shell in 1984 was extremely difficult for fisheries managers, and species specific catch amounts are limited. No data on numbers or weights of white abalone landed could be found prior to about 1990. Data available were temporally and spatially patchy, and reports were often contradictory. The conclusions that can bc drawn from the following treatment are somewhat limited.

The first abalone catch data reported for Mexico is from 1923, when a total of about 172 1 tons was harvested (Guzman del Proo, 1992). Of that amount, about 3.8 million pounds of all abalone species were exported to California (Cox, 1962, p 73). This export amount increased to 7.4 million pounds in 1929 (Cox, 1962, p 73). Due to vagaries in reporting, it is not known whether these figures are for meat only, or for animals in the shell, or are converted from meat back to animals.

More reliable commercial data reporting the landings of all species began in 1940 (**Figure 17).** The fishery was concentrated in Zones II-III of the coast (or Zones II-IV of Guzman del Proo, 1992). The harvest reached a peak of 6000 metric tons for all species in 1950. By the 1960's white abalone began to be fished more seriously (Cox, 1962). The total abalone catch declined, then remained constant at around 3000 tons between 1955 and 1976. In 1973 quotas were introduced for each cooperative in an attempt to limit the catch. Despite this, catch declined sharply after 1976, stabilizing again after 1984 at around 1000 tons per year. In response to the decline, size limits became actively enforced by requiring landing abalone in the shell. The fishing season is currently seven months in length, although the exact time differs by zone **(Table 12).**

The relative importance of each species varied between and within zones (Murueta et al., 1996). Most of the historical abalone catch was red and pink abalone although the fishery is currently supported mainly by pink and green abalone, which comprise about 95-98% of the commercial catch (Leon and Muncino, 1996). White abalone are reported to be a minor commercial species when catch for the whole Baja California region is considered (Leon and Muncino, 1996). Much of the Mexican species specific data is reported as percentage of the catch, and hot as absolute weights. Conversion to weight was not possible in most cases, as total weight was not provided with data. Species composition data from the total Mexican commercial catch between 1973 and 1990 were unavailable for this report..

White: abalone were harvested in Mexico before 193 I and although they were deep-living and probably hard to obtain, the fine tender flesh attracted the highest price (Croker, 193 I, p 69). The importance of white abalone in the catch varies with the scale of the harvest summary. White abalone have historically comprised only a few percent of the total Baja California catch (Leon and Muncino, 1996; Shepherd et al., 1998), but in single cooperatives and months, white abalone were sometimes important in the catch prior to 1973 (Table 13). In some months of the year, white abalone represented over 50% of the catch in Zone 1. The proportion of white abalone varied dramatically by zone during the 1970"s. In 1970 white abalone was 27% of the catch in zone I, while in zone II, white abalone was 0.5-20% of the catch between 1968 and 1984 **(Table** 14). In zone III white abalone was 3% of the catch in 1970 **(Table 14).** Quintanilla and Aceves (1976) reported the combined catch composition for all the Baja California cooperatives in 1973 (Table **15).** White abalone accounted for 17% of the catch in the first month of the 197.3 season, but in subsequent months was less than 2% of the catch. Although the total amount of abalone harvested per month was not provided, the decline in catch of white abalone as the fishing season progressed suggested that by 1973, depletion of the white abalone stocks occurred during, the fishing season. Overall, white abalone accounted for 2.8% of the total catch in the 1973 season (Quintanilla and Aceves, 1976). Shepherd et al. (1998) reported that the Natividad Island fishery for white abalone collapsed after only seven years, in 1976, and only occasional white abalone were harvested in subsequent years.

In small mainland cooperatives white abalone was occasionally a sizable fraction of the catch in the 1990's. For example, in the 1992 season white abalone was a rnajor portion (20-30%) of the catch of the Noroeste cooperative (Murueta et al., 1996). Similarly, from 1992- 1994, white abalone represented about 65% of the catch of one cooperative **(Table 16).** The total catch for that cooperative in that period was 26,301 kg of meat **(Table 17**), and 65% represents a large amount of white abalone meat (17,096 kg). This white abalone harvest may represent exploitation of a newly located reefs, and was not sustained in subsequent years, again suggesting that overharvesting had occurred.

Between 1990- 1997 white abalone was one. of the four species harvested at the 15 boat Natividad cooperative (Espinoza and Vega, 1997; Shepherd et al., 1998). The harvest was dominated by green and pink abalone (H. fulgens and H. corrugata), and has declined from 200 tons yr^{-1} in the 1960's to about 60 tons yr^{-1} in 1996 (Turrubiates and Shepherd, 1997). This decline is attributed to recruitment overfishing rather than environmental factors (Turrubiates and Shepherd, 1997), although in some years environment conditions may be important (Shepherd et al., 1998).

Catch data by species are available from 1990- 1997 for Zone I **(Table 18**). During this tirne green abalone accounted for 85% of the catch, while white abalone represented only 0.73% of the total harvest **(Figure 18).** There were no strong trends in terms of catch for any species **(Figure 19).** The proportion of each species taken in each month for the period 1990-1998 for Zone I shows that there is no seasonal serial depletion of species, as all are exploited approximately equally through the fishing season **(Figure 20).** The seasonal exploitation of white abalone is similar to the total exploitation pattern..No white abalone were harvested in Baja California Sur (Zones II-IV) including Natividad, from 1993 1998 (Julio Palleiro, Instituto Nacional de la Pesca Ensenada, pers comm.).

The percentage catch of each abalone species in both California and Mexico was calculated for the period of' time (1990- 1997) when comparable catch data were available

(Figure 21). In both countries white abalone were less than 1% of the total catch during this period **(Table 19).**

The effort in the Mexican fishery in terms of boats and divers is largely unknown. After 1974 reports mention that attempts were made to collect effort data and the number of days fished, but these appear to have been largely unsuccessful (Guzman del Proo, 1992). A typical day of effort for the team of three (diver, rower and deckhand) was 3-5 hours, including travel (Guzman del Proo, 1992).

In 1984 further attempts made to get dive effort data were similarly unsuccessful. Despite the limited information, in zones 11 and III CPUE appears to have declined from 205 kg/boat/day (1958) to 18 kg/boat/day (1984) (Guzman del Proo, 1992).
Since 198 1, the total Mexican catch has remained at around 800-1000 tons, with the majority coming from Cedros Is. (Leon and Muncino, 1996). Limited effort data from some cooperatives indicate that catch per trip varies dramatically between cooperatives, and does not allow a good comparison with earlier data **(Table** 17). The price of abalone in Mexico has remained approximately constant from 1993- 1998 (Julio Palleiro, Institut Nacional de la Pesca, Ensenada, pers. comm.) and is an important source of income for the region (Ponce-Diaz et al., 1998).

7.3. History of management regulations. Mexico.

7.3.1 Minimum size limits.

Prior to 1972, and perhaps beginning in 1956, the size limits were the same as for California (Guzman dèl Proo, 1992; Leon and Muncino, 1996). White abalone minimum size was probably 150 mm. A regulation requiring abalone to be landed in the shell for verification of size limit existed but was not enforced. Thus, a sizable fraction of abalone harvested were sub-legal size **(Table 13).** The closed season was from January 15 to March 15 (Guzman del Proo, 1992; Leon and Muncino, 1996).

In 1973 the closed season changed from winter (January 15 to March 15) to summer (July 1 to August 3 1) to irnprove protection of spawning pink and green abalone, however, this reduced the protection of winter-spawning white abalone. A system of catch quotas for each cooperative was introduced, and a second attempt to have abalone landed in the shell was made. Fishermen argued against this, citing transport and quality problems, and abalone continued to be shelled at sea (Guzman del Proo, 1992). At this time the minimum legal size for red, green and pink abalone was 165 mm, 150 mm, and 135 mm, respectively (Leon and Muncino, 1996). White abalone were probably captured at sizes greater than 135 mm, as required for pink abalone.

In 198 1 size limits and longer closed seasons were established by zones **(Table 12)** (Guzman del Proo, 1992). Present size limits in Mexico continue to differ by zone for the commercial species (**Table** 3). These are partially based on the animals having smaller maximum sizes. and research is now showing that the size at sexual maturity also differs between zones (**Table** 20) (Leon and Muncino, 1996), although the pattern is not as clear as the different minimum legal sizes would suggest. Thus, different size limits by zone arc supported (**Table** 20).

In 1984 the law requiring landing of abalone in the shell began to be enforced, and so observance of size limits probably increased (Guzman del Proo, 1992).

7.4. Conclusions. Mexico.

‘The conclusions that can be drawn from Mexican fishery-dependent data about the status of white abalone arc: weak. At times white abalone appeared to be a large fraction of the **catch,** and at other times an extremely small or non-existent portion.. This sporadic pattern suggests that occasional large catches may have resulted from the use of advanced technologies to locate deep reefs, or to the patchy distribution and susceptibility of the species to overharvesting. Some sizable catches were made in the 1990’s, and yet reports of overharvesting are common (Ramade-Villanueva et al., 1998; Shepherd et al., 1998). In general, however, it appears that the white abalone is a minor fraction of the commercial fishery in Mexico, and that it has declined slightly in percentage composition from 1970-1990. It is difficult to determine if this is due to a reduction in effort, or a decline abundance. Given the market demand for abalone in the United States and the Mexican economy, it is unlikely that there would have been a decline in fishing effort (Ponce-Diaz et al., 1998).

The white abalone fishery was apparently closed at Natividad in 1995 (Shepherd et al., 1998). In April 199’7, a proposal to close the red, black and white abalone harvest along the entire Baja California coast was submitted to Julia Carabias Lillo (La Secretaria de Medio Ambiente, Recursos Naturales, y Pesca) by Oscar Pedrin Osuna (director, Centro Regional de Investigacion Pesquera, Ensenada). This action was based on Mexican data (unavailable for this report) that showed these species were the least abundant of the Mexican abalone, and that densities had declined to a level at which recruitment failure was likely, or had already occurred, in sorne regions, As of March 10, 2000, this petition had yet to be acted on.

8. Estimated abundance of white abalone.

Estimates of the total white abalone population size can be made from both the fishery-independent and fishery-dependent data. An estimate of current white abalone population size from density data (fishery-independent data) is possible only in California. One problem will be accounting for the fraction of the population that was not sampled in surveys, the cryptic animals. If there has been little or no recruitment, as is likely for white abalone given the adult density and the scarcity of juvenile shells, then the cryptic fraction will be negligible.

8.1. Fishery-independent white abalone abundance estimate.

A fishery-independent estimate of total population size in 1997 of about 600 white abalone was made by Davis et al. (1998). This estimate was based on observed density from the California submersible surveys of 1996-97, and the fraction of the historic range in both California and Mexico that lay between 25 and 65 m (Table ‘7). Approxirnately 30% of the habitat covered in these surveys was deemed suitable for white abalone, however, the surveys were intentionally conducted in the most suitable regions. Only about 3% of the total area between 25 and 65 m is considered suitable (Davis et al., 199X). This estimate of 600 white abalone was made for the whole species range, including Mexico. Halving this figure, as there are approximately equal portions of the white abalone range in each county, the California population may only be 300 white abalone. If the catch data from Mexico are reliable., an estimate of 300 Mexican white abalone is obviously too low, as more than 12,307 kg of white abalone were harvested in Mexico Zone 1 during 1996 alone (Table 18). This amount of meat represents about half the live weight of the abalone, or 32,000 white abalone (conversion, 1.67 lbs per abalone (Pinkas, 1974), 2.2 lbs per kg).

Using the data from Davis et al., (1998), an estimate of total population size can be found by multiplying the observed density (0.000 167 ± 0.000 1, Table 2) by the fraction of the total area between 25-65 m that is considered to be suitable habitat (966 ha, 9,666,000 m^2, **Table** 7). The 1996/97 population size throughout the range is thus estirnated at 16 13 white abalone. Again, this figure may be too low given the Mexican fishery data.

8.2. Fishery-independent pre-exploitation abundance estimate.,

If the amount of suitable habitat has remained constant since the surveys of Tutschulte (1976), a fishery-independent pre-exploitation population estimate can also be made. Using the density estimate of 0.23 ± 0.29 m^{-2} (Table 2) and the habitat area of 966 ha (Table 7), a population size of 2.22 1,800 ± 2,80 1,400 whr te abalone prior to exploitation is obtained.

An estimate of the number of white abalone harvested can also be used to indicate approximate total size of the pre-exploited population if, as for white abalone, it appears that the whole population was harvested. In the ten year that the majority of white abalone were harvested in California (1969- 1978), approximately 605,807 pounds or 362,759 animals were collected (assuming 1.67 pounds per animal, Pinkas, 1974). Assuming that all legal sized adults were harvested every year, which is reasonable, as it takes 10 years to reach legal size, and the fishery collapsed after only ten years of effort, the average size of the adult California white abalone population prior to fishing was approximately 40,000 (total number divided by number of years fished). This does not include the white abalone from the recreational catch, which was a small fraction of the total (less than 5%). If instead the total catch is assumed to represent the total collection of accumulated virgin stock, and that there was no recruitment, the estimated former California population size equals the total catch from the ten year period, 362,759 white abalone. Doubling this figure, to include Mexico, leads to a California fishery-based estimate of 725,5 18 animals. This population estimate is obviously an underestimate, as some white abalone were collected in subsequent years and some animals were lost to natural mortality.

If the fishery-intlepcndent estimate of the pre-exploitation number of white abalone estimates is accepted, then the white abalone population in California has declined from some two million to about 1600 animals, or by 99.9%. We caution that these estimates of pre- and post-exploitation white abalone population size were based on limited and spatially separate surveys.

8..3 Abundance estimates from Mexican data.

In Mexico, fishery-independent surveys from 1968-70 were used to estimate the abundance of all abalone along the west coast of Baja California, using the length of the coastline, and the area of the seafloor estimated from charts to lie between 0 and 27 m (Guzman del Proo et al., 1976). This area was 6 12.5 km' . Total density was calculated as 0.05416 abalone m ^{2} from all the surveys, or 33.17 million abalone. Using similar logic, given that 35 of the observed 546 abalone were white abalone (6.41%), the estimated population size of white abalone along the Baja California coast, in the period 1968- 1970, was 2.12 million animals. Doubling this number to include California, leads to a Mexican fishery-independent pre-exploitation abundance estimate of 4.24 million white abalone. This estimate assumes that white abalone were found throughout the survey area, which is not true **(Table 11).** There is insufficient information to estimate the abundance of white abalone using only the region of Mexico that is white abalone habitat. No recent surveys in Mexico have been performed that would allow a fishery-independent population estimate to be made.

Using the same logic as for California and calculating the stock size using the fishery-dependent data for the period of exploitation prior to the 1990's is not possible in Mexico because the catch data are not given by species. Fishermen were not required to land the catch in the shell, so even retrospective analysis of shell discards is not possible. Some additional estimates have been made in Mexico for all species in some cooperative zones. White abalone were included in the estimates in only two of thirty surveys, and there is no way to convert these total figures to white abalone population estimates (Table 3 of Leon and Muncino, 1996).

8.4. Changes in abundance of white abalone.

The methods described above estimate that the total abundance of white abalone at the onset of exploitation in the early 1970's was 4.24 million, 2.2 1 million and 725,5 18 animals using Mexican fishery-independent, California fishery-independent and California fishery-dependent data respectively.

In summary, our analysis suggests that the pre-exploitation white abalone population numbered between two and four million animals. The current total population size based upon the best surveys to date is approximately 1600 animals. Even if the low estimate is correct, the population is currently less than 0.1% of the original size. More surveys to estimate densities in Mexico and the southern Channel Islands, especially San Clemente Island, are required before a more accurate population size can be determined. Given the remaining lifespan of the surviving white abalone in California, the amount of time required to perform additional surveys before taking action is excessive (Davis et al, 1998).

9. Potential factors in the decline of white abalone.

Six major causes for the decline of abalone in California have been identified. These are over-harvesting, mortality of sub-legal animals, illegal harvesting, predation (by sea otter range expansion), competition (from sea urchins), and loss of habitat (Henderson et al., 1988). Disease and hybridization may also be threats to the survival of white abalone.

Here we consider factors that may have led to the decline of the white abalone. Information on both white abalone and other abalone species will be used to judge the impact of each factor on the white abalone decline.

9. 1. Overharvesting.

Overharvesting by both recreational and commercial fishing has already been treated in detail (sections 6.2.2. and 7.2.2.). The practice of serial depletion observed in the California abalone fishery (Tegner, 1992; Davis et al., 1996) has lowered the density of white abalone adults to levels at which recruitment failure is highly likely, or has already occurred (Shepherd and Parrington, 1995). In the multi-species fishery of both countries, collecting the rare or incidental white abalone as they were encountered while harvesting the economically viable abalone species further reduced the population size after it was no longer viable to concentrate on white abalone harvest. The premium price for white abalone may also have encouraged exploitation to very low densities.

9.2. Mortality of sub-legal animals:

Abalone blood has no clotting ability, and cut animals bleed to death (Cox, 1962). Accidental cutting of sub-legal abalone is a significant cause of mortality (Burge et al., 1975) and may have further reduced the white abalone population size. Mortality due to cutting during collection of non-legal (short) red abalone was estimated at 60% from a half inch cut in laboratory experiments, and almost: 100% in the field (Burge et al., 1975, p 6). For the subtidal species, between 8.6% and 12.6% of legal size abalone were cut. The frequency varied with species, was highest in the most cryptic species, and lowest in the most exposed (Burge: et al., 1975, p7). The intertidal black abalone had lower cut rates, averaging 3.3% (Burge et al., 1975). The rate of cut "short abalone" is likely to be even higher as they are more cryptic than legal sized animals. Even animals that are handled and replaced without being cut suffer a mortality of between 2- 10% in the field (Burge et al., 1975, p 7). These animals are removed by predators such as sheephead and bat rays before they can reattach to the substrate. The cut rate was higher in winter, which may be due to increased water motion affecting divers during collection. Recreational divers also cut abalone at a greater rate, especially breath-hold divers, where the cut rate of legal sized abalone was over SO% (Burge et al., 1975 p 14). The cut rate may be reduced through education or policy, for example if only experienced fisherman can get a license, or by requiring that the first four abalone collected by recreational divers must be kept, with no replacement for large animals collected subsequently (Tegner et al., 1989). The shell collection data suggest that about 20% (estimated fraction of the 14 1- 1.50 mm class that appears to be above a smooth mortality curve) of animals died-just before legal size was reached (**Figure 3**), and sub-legal harvesting mortality is a likely explanation.

9.3 Illegal harvesting.

Intentional capture of undersized abalone may also have acted to reduce the population size. In some Mexican surveys a substantial portion of the commercial catch was found to be undersized (**Table** 13). In California, where the commercial catch has been landed in the shell for the entire period of exploitation, sub-legal capture is not likely to have been a major problem in the commercial Fishery. The amount of sub-legal harvesting by the California recreational fishery is unknown. Intentional capture of sub-legal animals before they make their full reproductive contribution has the potential to seriously reduce the population size of‘ white abalone.

Identifying the various abalone species has always been a problem for the fishery (Cox, 1960). Hence one species may be taken at the incorrect size if confused with another species. However, white abalone have the same size limit as the similar pink abalone, and are unlikely to be confused with the other species with smaller size limits (e.g. black abalone) due to location and physical characters. Thus, problems in species identification that led to sub-legal harvesting are unlikely to have been important in the decline of white abalone.

9.4. Predation.

Sea otters reduced population levels and sizes of red abalone after these mammal!; increased in abundance and range along the central California coast between about 1967- 197 1 (Wendell, 1994). Densities of red abalone declined by a factor of ten, and overall population size was estimated to have stabilized at 7% of pre-otter levels by 1993 (Wendell, 1994). This pattern also occurred as otters, moved further south to the Point Conception region (Laur et al., 1988). A similar otter-induced reduction in red abalone abundance has been suggested at San Nicolas Island (Haaker, 1994). However, a reduction in white abalone population size due to otter predation is not likely given its depth range and latitudinal distribution. Otters in California seldom forage below depths of 20-25 m, although 36 m foraging dives have been observed occasionally. In Alaska, however, otters have been recorded foraging to depths of 40 m (Estes, 1980; Riedman and Estes, 1988).

Predation by otters in shallow water!; on the less cryptic white abalone may currently restrict white abalone to depths below 25 m, or may have been a selective force in the past (speculation in Tutschutte, t 976, p 266). In general, with the exception of San Miguel and San Nicolas Islands, otters do not occupy the same range as white abalone. Otters were re-introduced to San Nicolas Island in 1987, well after the decline in white abalone abundance. Between 1987 and 1990, about 139 animals were transplanted, but only about 12% remain (CDFG report). As part of the San Nicolas Island reintroduction plan, otters that were found south of Point Conception were removed until 1993. In 19'95 the southern limit, excluding San Nicolas Island, was Point Sal, north of Point Conception (CEQA, 1997). In 1998, about 100 otters foraged along the coastline from Point Conception east as far as Isla Vista, Santa Barbara County (Haaker, personal communication). Nevertheless, otters cannot be responsible for the reduction in white abalone in the regions of the highest historical California catch, San Clemente Island and Cortez and Tanner Banks.

Other observed abalone predators include asteroids (Pycnopodia, and Astrometis), fish (Scorpaenichthys, Myliobatis, and Semicossyphus), crustaceans (Panulirus, Cancer, and Loxorhynchus), and octopuses (Octopus spp.) (Croker, 193 1; Bonnot, 1930; Tutschulte, 1976; Howorth, 1978; Tegner et al., 1989). Increases in the abundance of these predators might also correlate with declines in white abalone abundance, however, density information on these species in white abalone habitat has not been collected. In shallower waters, surveys have not detected increases in the density of potential abalone predators (Davis et al., 1996).

9.5. Competition.

The urchins Strongylocentrotus purpuratus and S. franciscanus are potential abalone competitors (Tegner and Levin, 1982; Davis et al., 1992, Guzman del Proo, 1992). The abundance of these competitors may impact the amount of algae available for abalone consumption. It has been suggested from laboratory studies that when algal drift is abundant, red abalone may out-compete red urchins (S. franciscanus, which have reduced growth), however, the reverse is true under conditions of low algal abundance (Tegner and Levin, 1982). There are no field studies on competition for food or space between abalone and urchins or other competitors. S. franciscanus is also the most likely competitor, but it is not abundant in the central portion of the Baja peninsula (Guzman del Proo, 1992). The gastropod Lithopoma (Astrea) undosa is another possible abalone competitor: trends in its abundance are unknown, although it too is harvested in some portions of the white abalone range. With the low (density of potential competitor species and abalone due to harvesting, competitive interactions are no longer likely to exert a strong effect on population dynamics.

Urchins may not only act as abalone competitors, but also act as facilitators. Red urchins with their large spine canopy may provide physical protection for juvenile abalone (Tegner and Dayton, 1977), and may also enhance settlement when their grazing maintains coralline algal patches, which have been shown to result in increased settlement (references in Tegner and Levin, 1982). Again changes in facilitator density throughout the range of white abalone are unlikely to have led to the observed decline.

Abalone may also compete with congeners for algal material. This is unlikely between the various California abalone species, due to spatial separation by depth and range. White abalone were one of the last species to be exploited, all southern California abalone are in decline, so competition with another abalone species leading to a reduction in white abalone seems unlikely.

If white abalone were ever actually at adult densities of 1 m^{-2} (Tutschulte, 1976) and moved over the rock substrate looking for food, they may have reduced the survival of settled conspecifics. It is important to note that adult and juvenile abalone occupy different microhabitats (exposed on tops of rocks and cryptic on the underside of rocks respectively), and so interference competition is unlikely. There is some evidence that at high densities reduced local settlement occurs, presumably due to bulldozing of new recruits (Shepherd and Partington, 1995). Tutschulte (1976) claimed in his Introduction to have found evidence for density-dependence, but this claim was not substantiated by data. At the current white abalone: densities, density dependence is highly unlikely. The available evidence suggests that white abalone competitors are not likely to have led to decline in population size.

9.6. Habitat loss

The amount of suitable white abalone habitat can only be estimated at this time (**Table** 7). Natural or anthropogenic white abalone habitat losses are unknown. The isolated position of the Channel Islands and the depth of white abalone habitat should limit the effects of anthropogenic habitat alteration, such as pollution (Tegner et al., 1996). In contrast, along the mainland of California pollution did lead to loss of shallow water abalone habitat (Macrocystis kelp forests) along the Palos Verdes Peninsula in the 1950's-1960's. This in turn led to the decline of some shallow water abalone populations (Tegner, 1989, 1993). The source of pollution has since been controlled, and the habitat is not currently impacted (Tegner 1993).

Habitat can also be lost through climate change. For example, changes in ocean conditions may affect larval stages and adult abalone. Long-term increases in surface water temperature in the eastern Pacific Ocean have been documented (Roemmich and McGowan, 1995; Hayward, 1997). The frequency of short-term warming events has also increased since 1977 (McGowan et al., 1998). El Nino conditions raise surface water temperature above the level white abalone larvae survive best. However, these events are periodic and are not expected to lead to total recruitment failure. Warmer temperatures have been observed in white abalone habitat (Dan Richards,, pers. comm.), but without long-term records, their significance is unknown. Long-term increases in surface temperature have moved the average temperature closer to the optimum laboratory white abalone larval survival temperature of 18°C (Leighton, 1972). Thus, while a change in water temperature at depth has not been adequately documented, the change in surface temperature (and hence at depth) should not directly lead to a decline in larval survival; in fact it should lead to an increase in survival as water temperature approaches 18°C. Diseases that could affect adult white abalone may also be more likely in warm water (see following section). During El Nino conditions, warm water is associated with depleted nutrients, and declines in both the Macrocystis canopy and the availability of drifting material. This means lower food levels for adult abalone in shallow waters, which results in poor condition (Tegner, 1989). The effect of temperature increases at depth, either directly on white abalone or on algal abundance, is unknown.

Harvesting of Macrocystis pyrifera has been shown to have little effect on shallow-living abalone species (Tegner, 1989). Harvesting has been hypothesized to even benefit shallow species by providing greater amounts of drift. No effects of harvesting are likely for the deep-living white abalone, which occur largely below the depth of Macrocystis forests. Habitat loss is unlikely to have been responsible for the dramatic reduction in white abalone population size.

9.7. Disease

One disease known to affect west coast abalone species is withering syndrome (WS), first detected in 1985. WS has devastated black abalone populations, and there is evidence that WS also occurs in pink, red and green abalone (Altstatt et al., 1996, p 190, 191). Experiments have shown that WS is not directly caused by warm water, although this speeds up death in affected individuals, which is associated with a ricksettia-like bacteria that affects the digestive glands (Friedman et al., 199'7). The mass mortalities associated with the outbreak of WS in black abalone population:< resulted in large numbers of shells which were easily detected in surveys (Haaker, pers. comm.). If white abalone were affected in large numbers, large numbers of shells or affected individuals of all size classes would have been detected in the surveys of the early 1980's. WS may affect white abalone at lower frequency, but this would not lead to the large decline in abundance observed in the 1970's. Twenty freshly-dead, undamaged white abalone shells were collected from Farnsworth Bank, Santa Catalina Island in 1990, and may have been killed by disease (Tegner et al., 1996). Two live white abalone with WS were collected from

Santa Catalina Island in 1993, and examined by experienced collectors (Haaker, unpublished data). WS does not always lead to mass mortality; even with a 5% level of WS infection of red abalone at San Miguel, the population is apparently stable (Haaker, pers. comm.). After considering the evidence, we conclude that disease was not likely to have led to the decline in abundance of white abalone.

9.8. Hybridization

Natural hybridization between California abalone species occurs (Owen et al., 1971). Hybrids have been recognized on the basis of morphological characters (Owen et al., 1971) and laboratory crosses (Leighton and Lewis, 1982). Genetic studies of hybridization have not been performed for the California species. Hybridization of white abalone with other more abundant abalone species could act to lower population size.

Six of the seven California abalone species considered by Owen et al. (197 1) did hybridize. Apparently H. cracherodii does not hybridize, even though in the Swanson and Vacquier (1998) phylogeny it is not the least related species **(Figure 1). Of** the fifteen possible combinations between the six species studied by Owen et al (1971), 12 hybrid combinations were found. Species that produce hybrids with H. sorenseni are H. walallensis H. k. assimilis H. rufescens, H. corrugata, and H. fulgens. Hybrids between red and white abalone were tihe most common, while H. fulgens (green abalone) is the least common hybridizing species (Owen et al., 197 1). Hybrids between pinks and whites (the two most unrelated species according to **Figure 1**) have been reported (Ovven et al., 197 1). One of the paratypes of white abalone held in the 'LA county Museum is now recognized as a hybrid (Owen et al., 197 1). The success of hybrid crosses, in terms of fertilization success, varied between species, White and red abalone crosses had successes of 96%, while those between other species averaged 10-36% (Leighton and Lewis, 1982).

Frequency of "adult" abalone hybrids in the field is low, occurring in 0.02-0.37 % of the commercial catch considered by Owen et al. (197 1). Of course the actual frequency of hybridization events may be higher, but survival to adulthood lower. Disturbance, high urchin frequency, and low abundance of one parent species increased the frequency of hybrids (Owen et al., 197 1). This may have an impact on white abalone, especially as it may remain at low density for some time into the future. White x red hybrids are found at shallower depths than the pure whites, from 25-80 feet (Owen et al, 1971). This may be due to different temperature tolerances in hybrid larvae or adults. The formation of hybrids seems to require 10 times higher sperm and egg densities than for homologous fertilization (Leighton and Lewis, 1982; Hooker and Morse, 1985). Hybridization is unlikely to have led to the decline of white abalone, as large numbers of hybrids were not found, and at this time hybridization is considered to be a rninor threat to the persistence of the species.

10. Implications of low population size for white abalone.

The minimum viable population size for other abalone species is based on a combination of density and population size. This population size was estimated at 1000 abalone (about 50% of the unfished population size) for a small isolated area studied by Shepherd and Brown (1993).

The effect of reduced genetic diversity brought about by low population size on abalone population survival is unknown.

Once reduced to low population size, white abalone face further limits on survival and reproduction. Reduction in reproductive success below some threshold density is also known as an Allee effect. The removal of large animals and reduction of densities have been recognized as threats to the survival of various abalone species for a long time (Edwards, 1913a, p 1 1). Densities of white abalone are too low to permit successful fertilization, and have probably been too low since the decline of the commercial fishery in 1978. Densities required for spawning have been determined mainly for broadcast spawning sea urchins (Pennington, 1985; Levitan et al., 1992; Levitan and Sewell, 1998), but are equally applicable to abalone. A field study of H. laevigata showed that fertilization success was related to separation of individuals, and fell below 50% as densities declined below 0.15 m^{-2} (Babcock and Keesing, 1999). Current densities of white abalone in California, less than 0.0002 m^{-2}, are far below this threshold.

Natural aggregation during spawning may overcome some problems with low abundance and has been demonstrated for two abalone species (H. laevigata and H. kamtschatkana) (Breen and Adkins, 1980; Shepherd, 1985; Shepherd and Brown, 1993). This behavior may increase density temporarily, but at low overall densities, even these species do not aggregate to sufficient local densities for high fertilization success. It is unknown if spawning aggregations occur in white abalone. In any case, the densities of white abalone are currently too low for aggregation to be successful.

Other behavioral patterns besides aggregation may raise fertilization success. Spawning during minimum water movement has been suggested for H. rubra (Prince et al., 1987), which has been shown to halve larval recruitment correlated with adult density (McShane et al.., 1988). One explanation for this is recruitment from local larval production, another is attraction of larvae to conspecific adults. Larval tows have been largely unsuccessful in resolving these two hypotheses; the abundance of abalone trochophore larvae is often very low, even after observed mass spawning (Breen and Adkins, 1980; McShane et al., 1988). Absence of larvae in the plankton may be indirect support for hypotheses favoring local recruitment.

Models and experience suggest that for sustainable abalone fisheries, egg-per-recruit production (EPR) should not drop below about 40% of the unfished stock before crashes are likely (Shepherd et al, 1995). It is possible to calculate the EPR for a population, and see if the fishing pressure is too high for a particular management scheme. Given that about 80,000 white abalone were harvested in the peak year, 1973, and about 360,000 in ten years of the California fishery, the current population size in California represents an extreme case of population reduction, which is highly likely to impact EPR.

When densities of the Australian abalone H. laevigata fell below 0.20-o. 15 m^{-2}, a greater risk of recruitment failure was observed using stock recruitment curves (Shepherd and Brown, 1993; Shepherd anti Parrington 1995). White abalone, with estimated densities of' less than 0.0002 m^{-2}, are well below the level at which recruitment failure has been observed in other abalone species.

Remaining white abalone have completed most of their expected lifespan. Haaker (1994) estimated that the time left to save this species, if no more natural reproduction occurred, was 10 years. This estimate was based on the estimated maximum age of 35-40 years (Tutschulte, 1976), and the time of the last known recruitment success in 1966. If this approach is accepted, white abalone that survive from that recruitment would be 35 in 2001, and 40 years old in 2006. Declines in abalone fertility with age are unknown, but are a potential concern, and further stimulus for fast action.

There has been slow recovery of other abalone species reduced to low numbers in some areas, such as the green abalone population at Palos Verdes (Tegner and Butler, 1985a; Tegner, 1992; Tegner, 1993). In addition to the problems of low density discussed above, recovery there was inhibited by poaching, as even transplanted animals were lost, with no s'hells remaining to implicate natural predators. Enforcement and public education will be vital to ensure protection and the recovery of white abalone. Aggregation of a small stock may make them more vulnerable to poaching (Henderson, et al., 1988), and careful site selection should take place to minimize that risk. Illegal harvest or poaching can make a significant impact if it occurs at low population sizes, or when the few remaining animals are aggregated. Protected rare species may also be incidentally taken if they are confused with more common species, but all fishing is presently closed in southern California. Even if human intervention is deemed unnecessary, measures to protect against illegal harvest of white abalone should be a priority.

White abalone will almost certainly [illegible] human assistance to avoid extinction. The estimated population size for white abalone throughout its range is too small to allow a natural recovery. The densities are too low for natural fertilization success.

11. Factors important for abalone management.

"Conservation laws provide ample protection for abalone" (N. B. Scofield, Director of the Bureau of Commercial Fisheries, 1930).

Management practices in abalone fisheries include commercial harvesting only (e.g. Mexico), recreational only (e.g. northern California), and both commercial and recreational (e.g. Tasmania). Harvesting techniques are in turn often regulated, and include shore gathering only (H. tuberculata in Europe), no scuba (northern California), and scuba and hookah (central and southern California). Regulating harvest techniques allows some control over fishing effort. The method of collection may also impact the survival, and is regulated, e.g. the damage inflicted while harvesting sub-legal animals discussed earlier.

In addition, most abalone fisheries are managed with the belief that a minimum size limit will protect the resource (Scofield, 1930; Tegner et al., 1989). Minimum size is set above the size at sexual maturity, allowing for several years of reproduction before recruitment to the fishery. This has been determined on a somewhat adhoc basis, selecting a minimum size limit that most animals will attain on the basis of tagging data (Burge et al., 1975, p9). Tagging data provided estimates of growth rate, and time to reach sexual maturity.

Before closure of the major California abalone fisheries, there were two minimum size limits for five of the species (**'Table** 3) (Tegner, 1989). The smaller size for each species was established for recreational divers, while the larger size was set for commercial harvesters. This two--size policy was established in 1921, as the recreational fishermen argued that the: deep water commercial harvest was removing animals that would have eventually migrated to shallow water replacing the populations removed by the recreational catch (Scofield, 1930; Cox, 1962, p 96). Such an ontogenetic migration has not been supported by any studies (Scofield, 1930).

The size limit of white abalone when they were fished commercially in California was 159 mm (recreational limit was 153 mm) (**Table** 3). The minimum size of animals available for harvest (153 mm) occurs about 10 years after sexual maturity (about 50 mm), if the figure of adult growth of 10 mm yr^{-1} is correct (Tutschulte, 1976; Tutschulte and Connell, 1981). 'Thus, animals available to the fishery are about 13- 14 years old. The white abalone minirnum size was chosen by comparing the size of white abalone to the pink abalone (Burge et al., 197.5). No consideration of potential differences in the biology of the white abalone was made in establishing this size limit.

Size limits apparently are not adequate to protect a fishery if sufficient spawning densities are not maintained, and the only way to do this may be through closed regions (Shepherd and Brown, 1993). If there is limited larval dispersal (10's of meters according to Prince et al. 1987, or 100's of meters to kilometers according to Tegner, 1992 and Shepherd and Partington, 1995), then refuges may not act as source areas if the separation is too great (Shepherd and Brown, 1993). However, it is hard to manage reserves if they are too close, and interspersed with open fishing areas.

Other factors should be considered when managing a commercial abalone fishery. While too late to prevent the decline of white abalone, the following should be considered in a recovery plan and for future management.

Regions fished.

Dividing the fishing region into blocks as in California, or zones and cooperatives in Baja California, allows different management schemes to be implemented for different regions. If accessibility varies., fishing effort may also be manipulated through such divisions.

Species identification.

In multi-species abalone fisheries, the same management may not be appropriate for all species, and species identification for harvesting and reporting should be mandatory.. Species are not always identified in landing reports, but it is critical for better management, as is accurate reporting of the harvest location.

Reserves and/or long-term closures.

The importance of reserves in maintaining stocks has been suggested for many years (Edwards, 1913a, p 12; Davis et al., 1998). However creation of reserves following depletion of stocks is not always sufficient to replenish stocks. Long-term closure of one region, the Palos Verdcs Peninsula (since 1977, Tegner and Butler, 1985a), following abalone decline did not lea(to a recovery of local abalone stocks. although lack of enforcement of the protected region may have been responsible (Tegner, 1993). Little is known about the size of closed areas necessary for local recovery or to act as a larval source for other areas. Areas open to fishing can also be rotated to allow recovery of depleted stocks (Sluczanowski 1986).

Seasonal closures.

Shorter fishing seasons allow fishing effort to be regulated, and may be set to protect the abalone during the spawning period, when animals may become behaviorally more vulnerable to harvest through aggregation or location. Winter closures may reduce the frequency of cut abalone due to rough conditions and poor diver control while harvesting (Burge et al., 1975). The seasonal closures used in the management of the southern California abalone fishery were inadequate to protect the resource.

Time of legal abalone fishing.

California abalone may only be harvested one-half hour before sunrise to one-hall' hour after sunset. This law was created in California in 1974, and was designed to prevent harvesting while animals are in the vulnerable feeding position or location (Burge et al., 1975).

Licensing.

A variety of licensing techniques has been used in Australia in attempts to control the catch and effort. Unfortunately CPUE changes dramatically with changes in license policies (Prince and Shepherd, 1992), making their effectiveness difficult to determine.

Resource ownership.

Ownership of the resource may lead to better management by the owner-harvesters (Edwards, 19 13a, p 12; Prince and Shepherd, 1992). This strategy may avoid the problem of the "tragedy of the commons". Similar patterns of resource ownership to those associated with terrestrial production may lead to greater sustainability of abalone fisheries in the future.

12. Conclusions: current status of white abalone.

There has been a greater than 99% decline in both the abundance and density of white abalone in California since the 1970's (**Table 2).** The magnitude of the decline in Mexico is less well known, hut a serious decline has certainly occurred. The abalone fishery contributed to the decline of white abalone by overharvesting, and reducing the density to the point where recruitment success has been unlikely. The fishery in both Mexico and California saw a decrease in landings due to lack of white abalone, not a reduction in effort. Other factors considered were unlikely to have caused the decline in population size of white abalone. Recruitment overfishing is likely to have led to the decline in the white abalone populations of California and Mexico.

The risk of extinction for white abalone is extremely high if the present estimates of density and the age of surviving animals are correct. Even if the population size estimates are too low, it is the density of surviving adults that is critical, not the overall population size. The density estimates obtained from surveys to date show that white abalone density is currently too low to permit successful recovery. This species may become extinct in 10 years as old animals die of natural causes.

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Figure 1. West coast abalone classification and phylogeny based on sequencing of the egg receptor for lysin. Data from Swanson and Vacquier (1998). In another phylogeny black abalone rather than pink are the least related species (Lindberg, 1992).

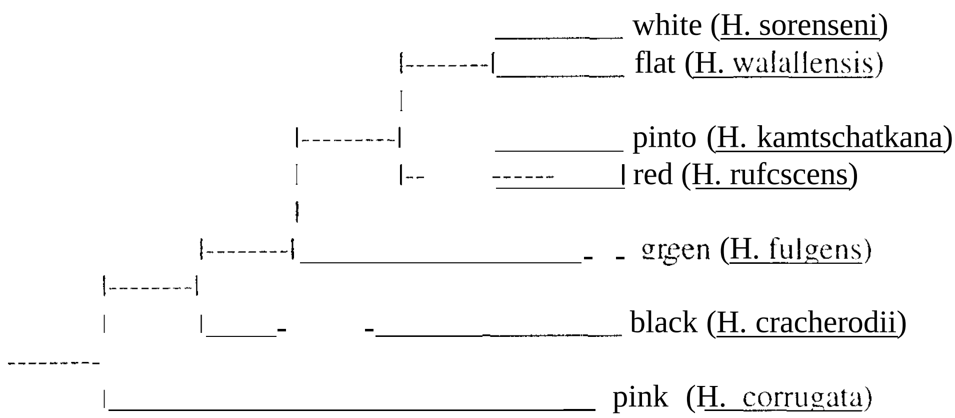


Figure 2. Map showing west coast locations discussed in this document.

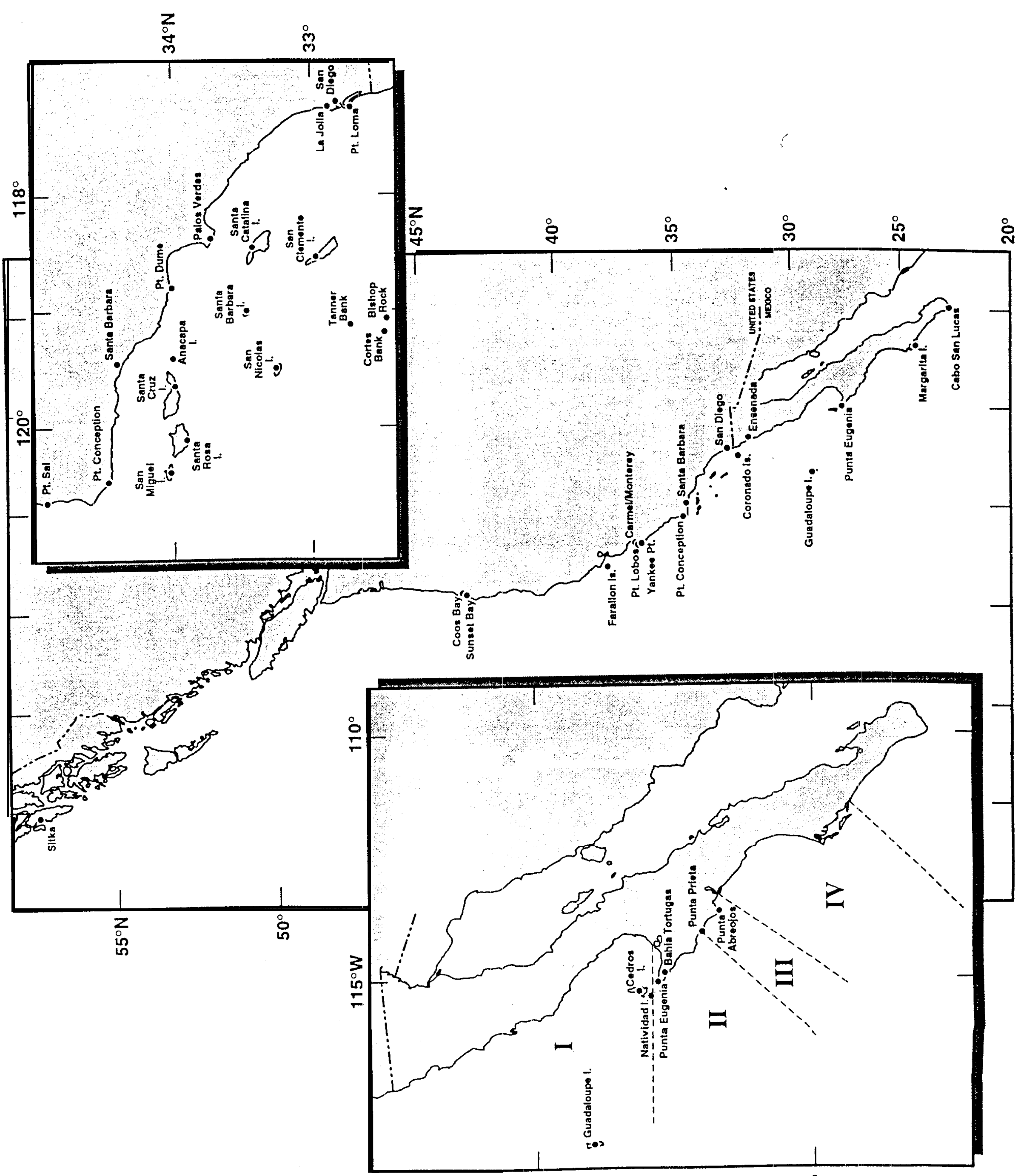


Figure 3. Size frequency of white abalone (live and empty shells) found during 1992-1993 California Channel Islands diving surveys targeting white abalone habitat (data from Davis et al., 1996). The minimum size for harvest is 153 mm. Note the peak in shell abundance in the size class below the legal size class, which may be due to mortality of bar-cut sub-legal animals.

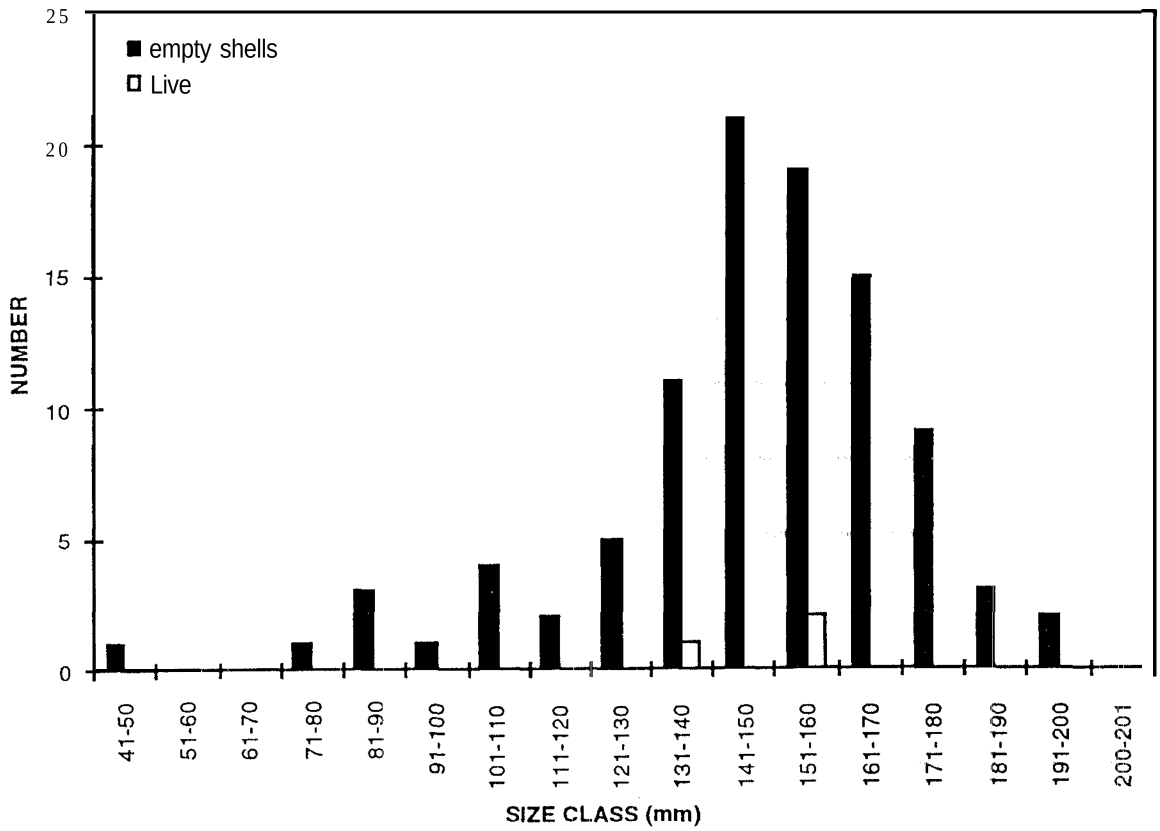
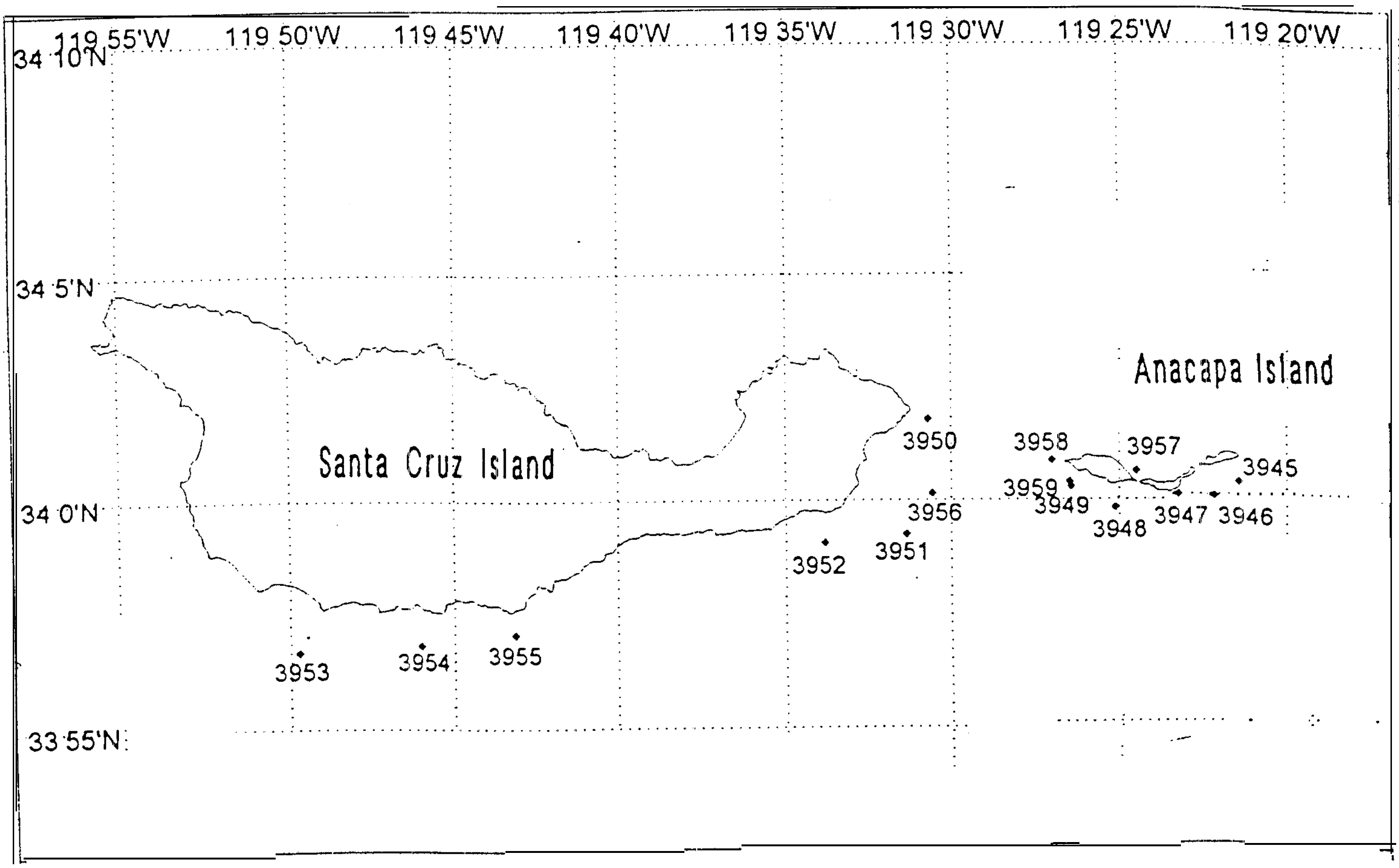


Figure 4. Location of submersible dives in white abalone habitat at two of the northern Channel Islands (Santa Cruz and Anacapa) and Santa Barbara Island in 1996 and 1997. Exact locations and dates for each dive number are provided in **Table 6.**



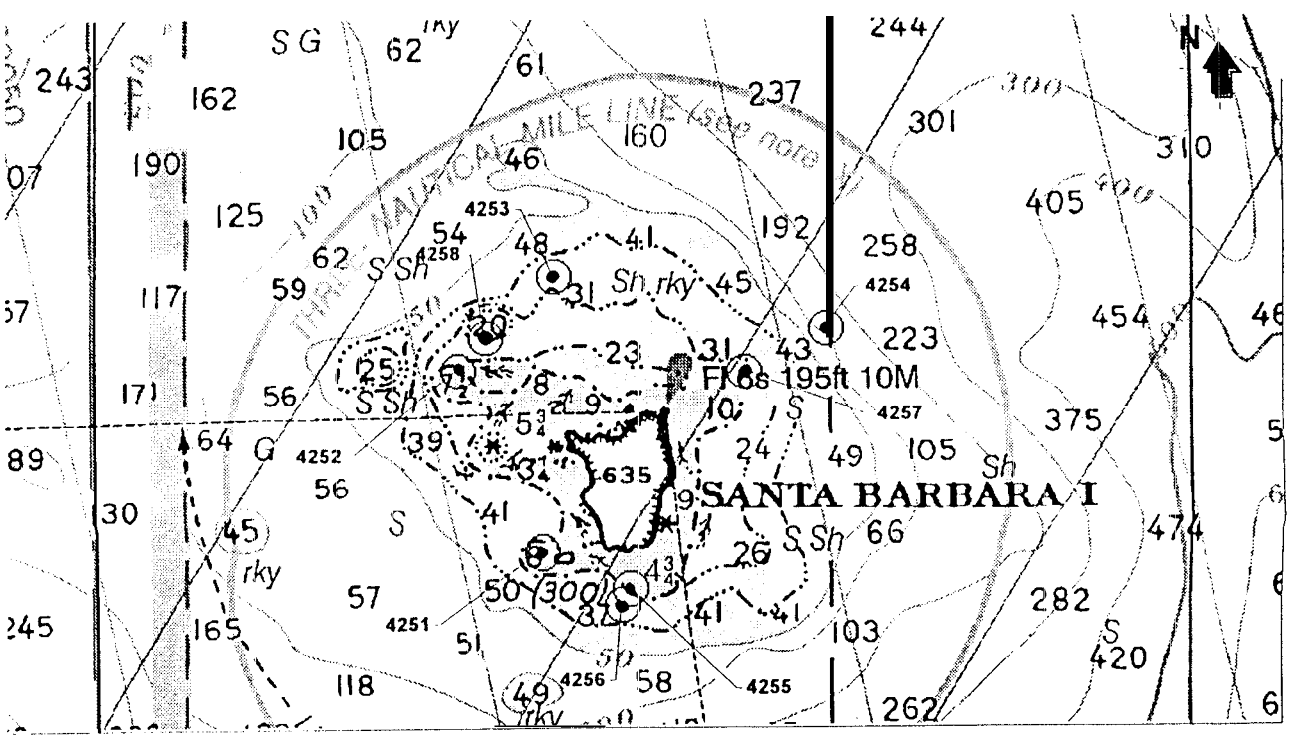


Figure 5. Total commercial landings for the five abalone species harvested in California from 1915 to 1997, when the moratorium on all commercial harvesting began. Data from California Department of Fish and Game (CDFG).

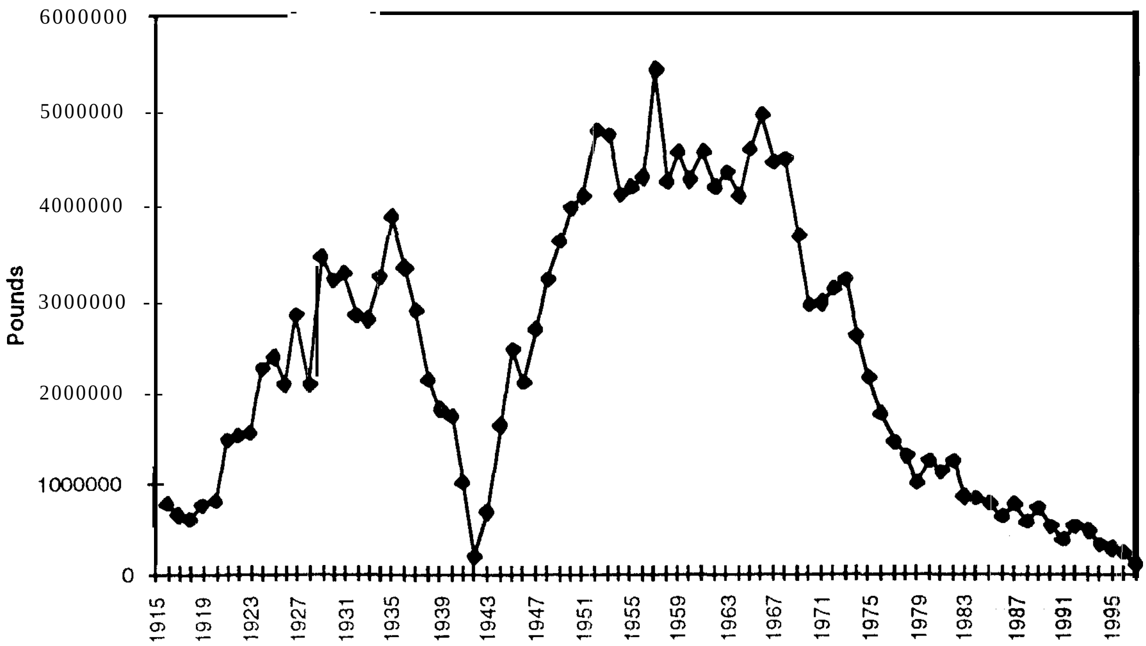


Figure 6. California commercial abalone fishing effort. Prior to 1972, commercial permits did not distinguish between divers and tenders. Data from CDFG, and Lundy (1997).

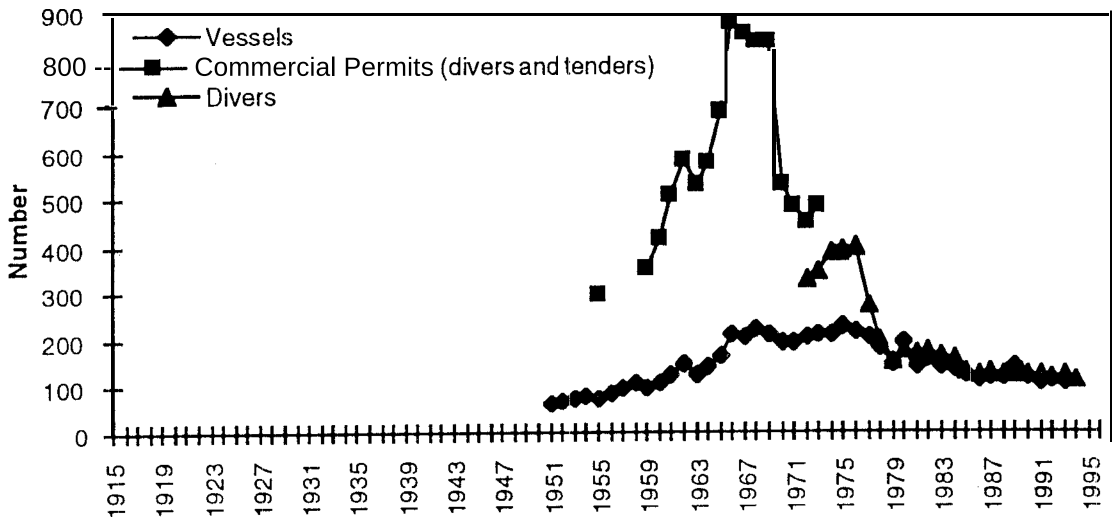


Figure 7. California commercial abalone landings (weight in shell) by species, 1915-1997. A. Red and pink abalone. B. White, green and black abalone. Note the ‘difference in scale between panels, and that the peak years of landings for each species are different, suggesting serial depletion. Landings for white abalone alone are also shown in Figure 9. Data from CDFG.

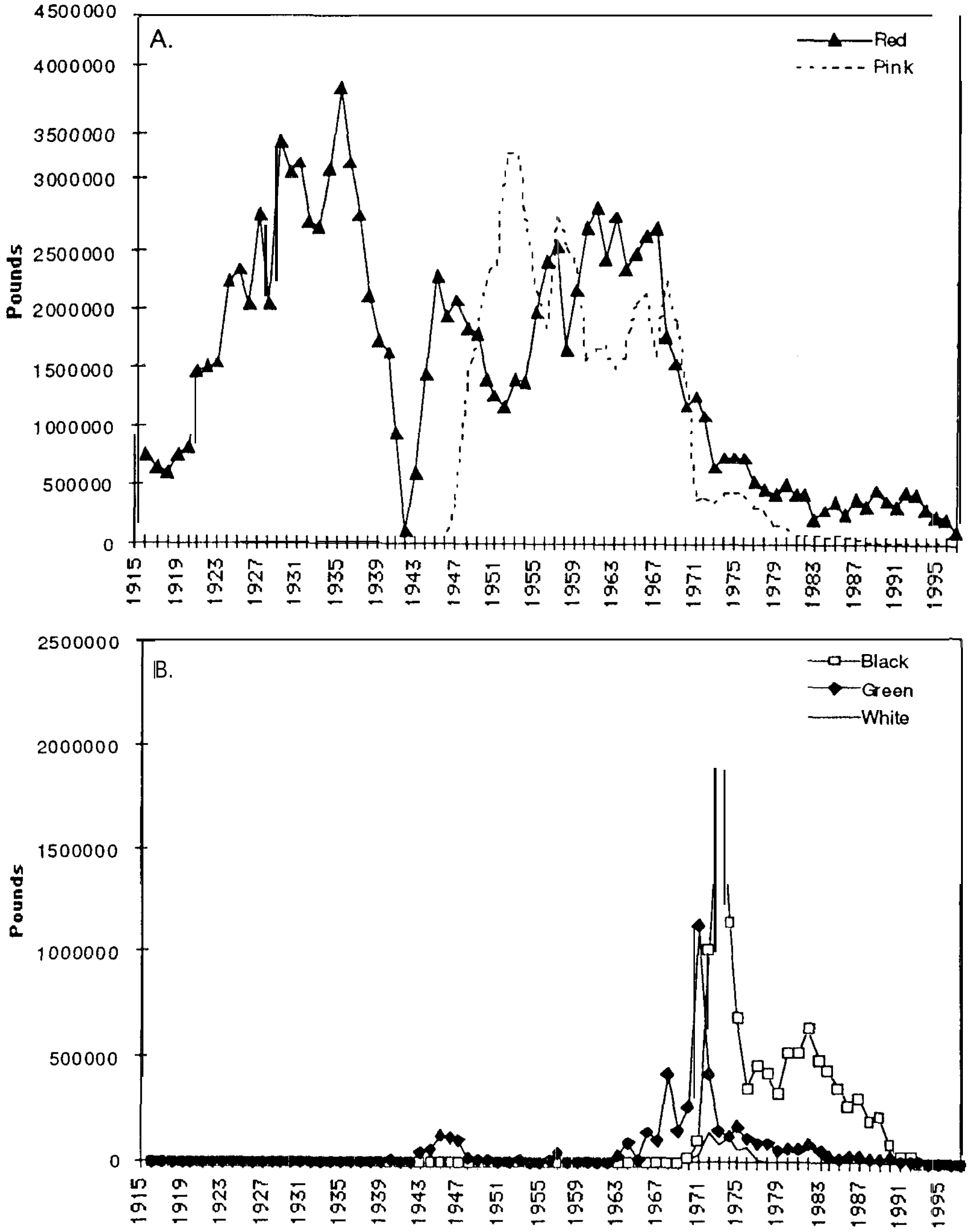


Figure 8. Composition of the California commercial abalone catch (weight in shell) for the period 19 15-1997, by species. The percentage of the total catch is shown above each species bar. Data from CDFG.

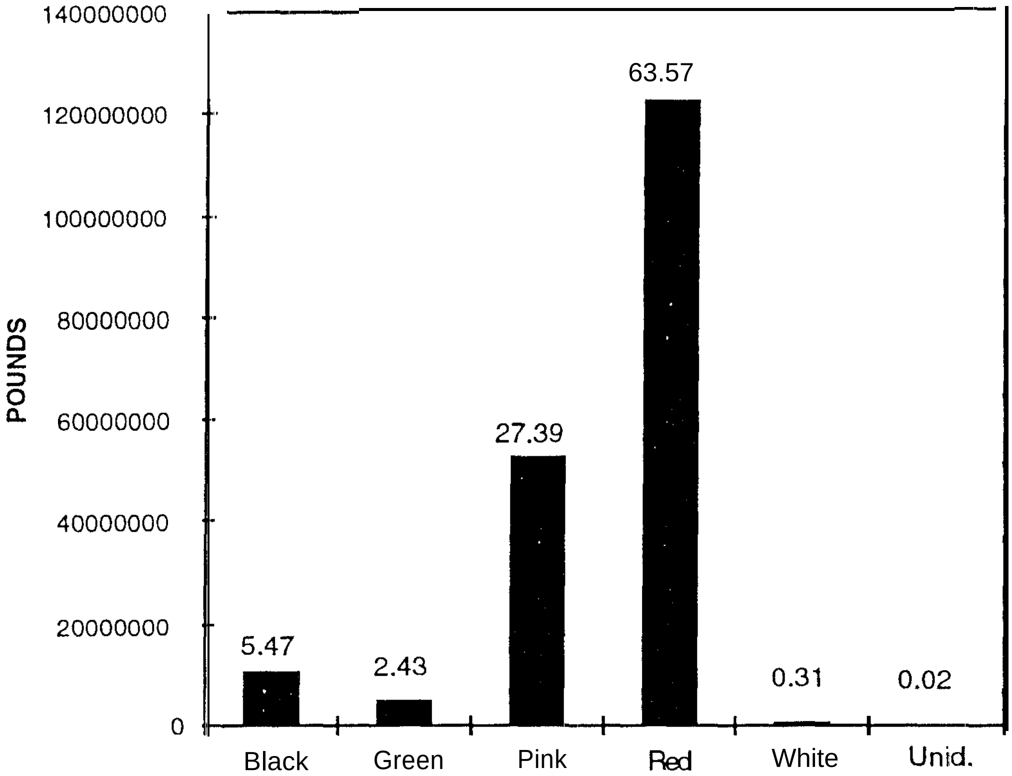


Figure 9. California commercial catch (weight in shell) of white abalone reported in CDFG bulletins for the period 1955-1997. The same data shown in panel B, but the y-axis is logarithmic to better illustrate the decline of the fishery. Data from CDFG.

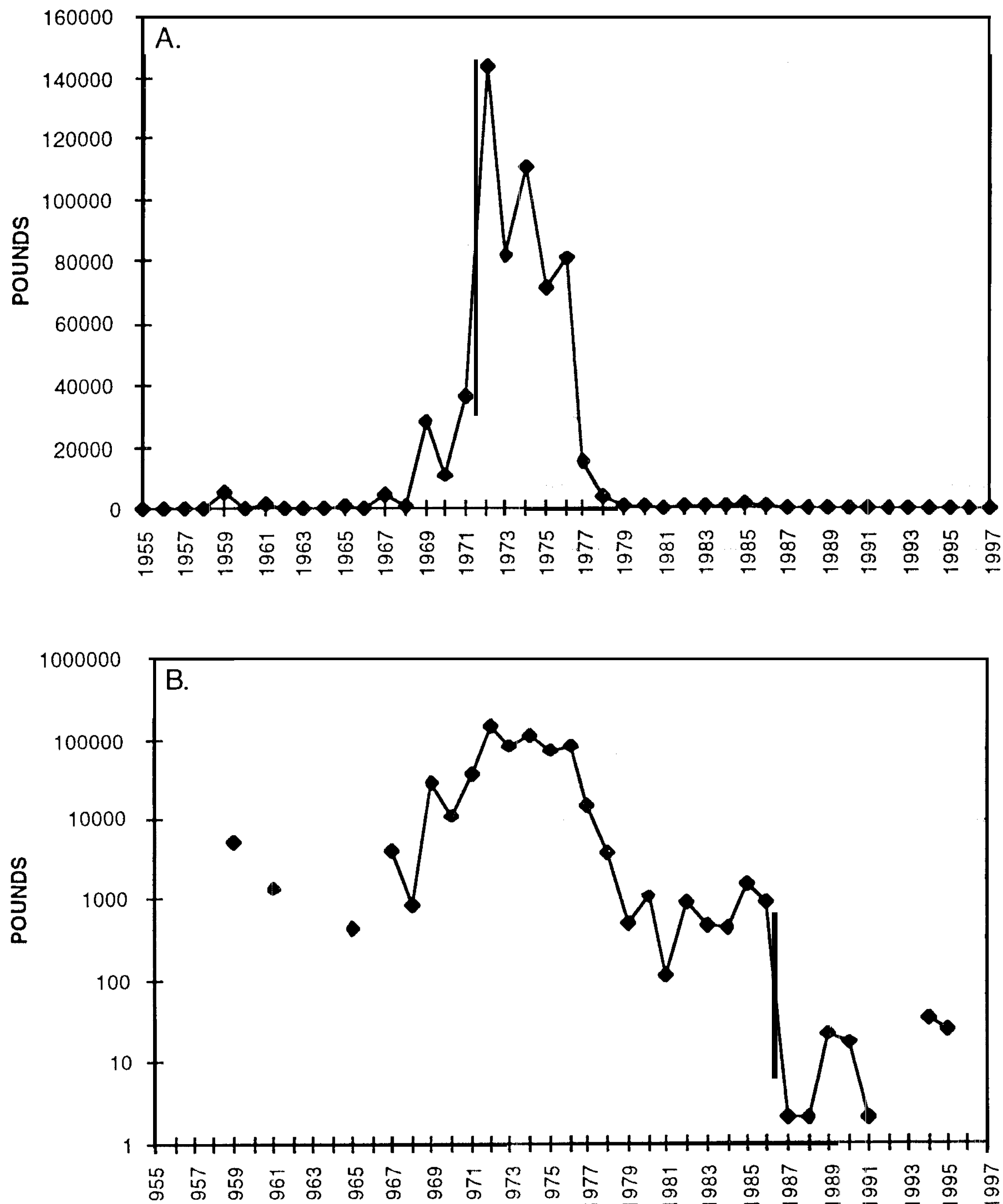


Figure 10. California commercial white abalone total landings (weight in shell) each month for the period 1965- 1995. The months of February and August were closed early in the period to "protect" spawning stocks. Data from CDFG.

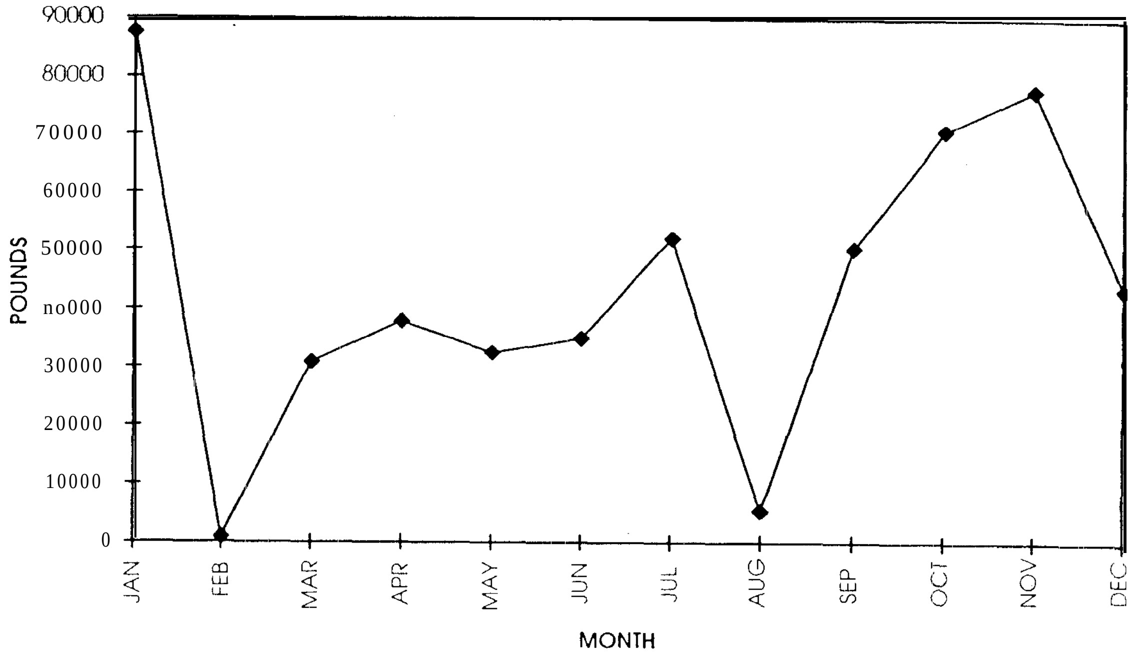


Figure 11. Commercial white abalone landings in California (weight in shell) by region from 1955- 1993. The three columns for the mainland regions also include a port location, and so landings in these regions may also include abalone that were collected elsewhere and just unloaded at that location. The last column to the right represents landing regions that are obviously incorrect, such as one instance of white abalone landed at Mendocino County. The percentage of the total landings from each location is shown above each column. Data from CDFG.

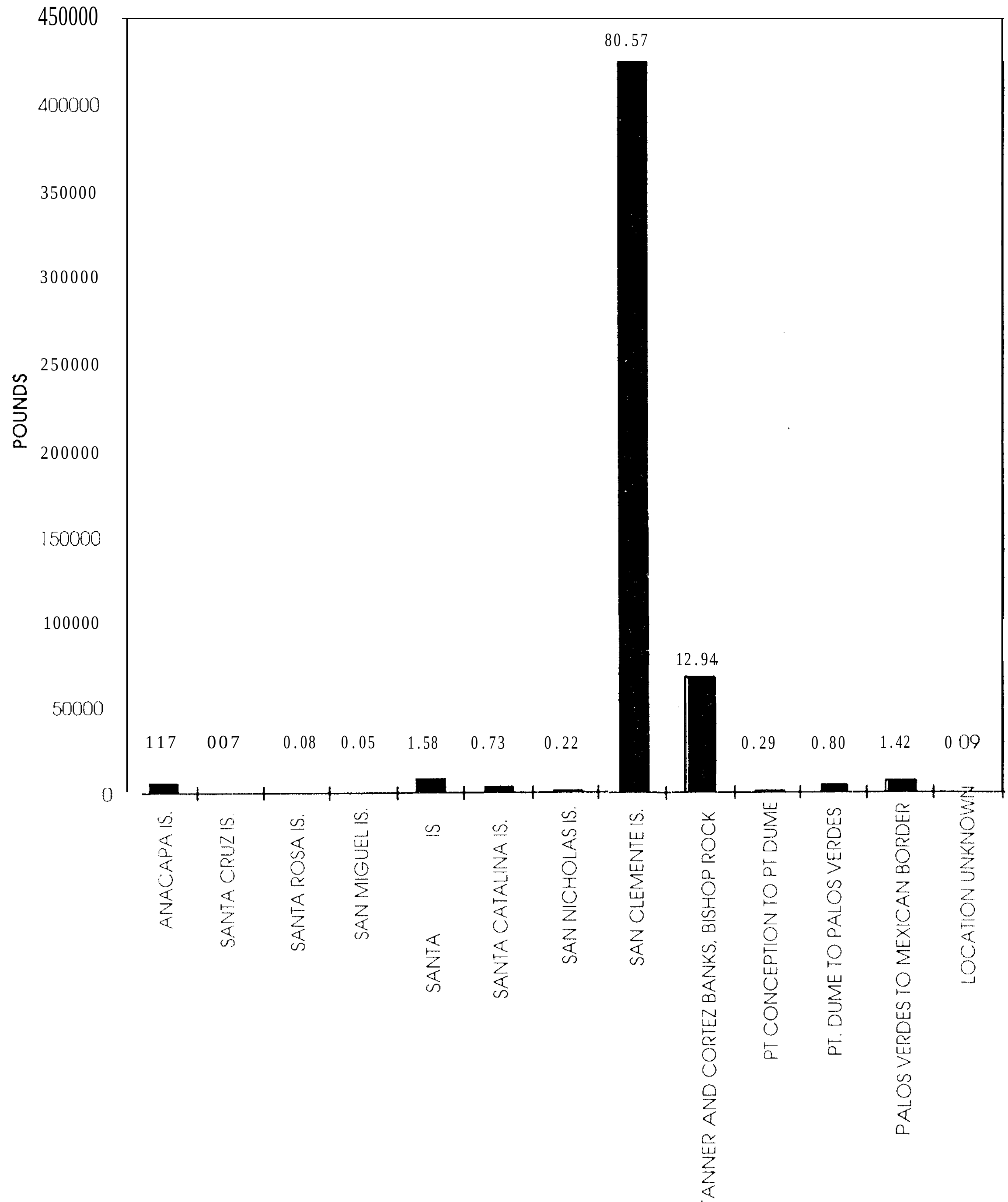


Figure 12. California commercial landings (weight in shell) and total value for all abalone species from 1915-1997. Data from CDFG.

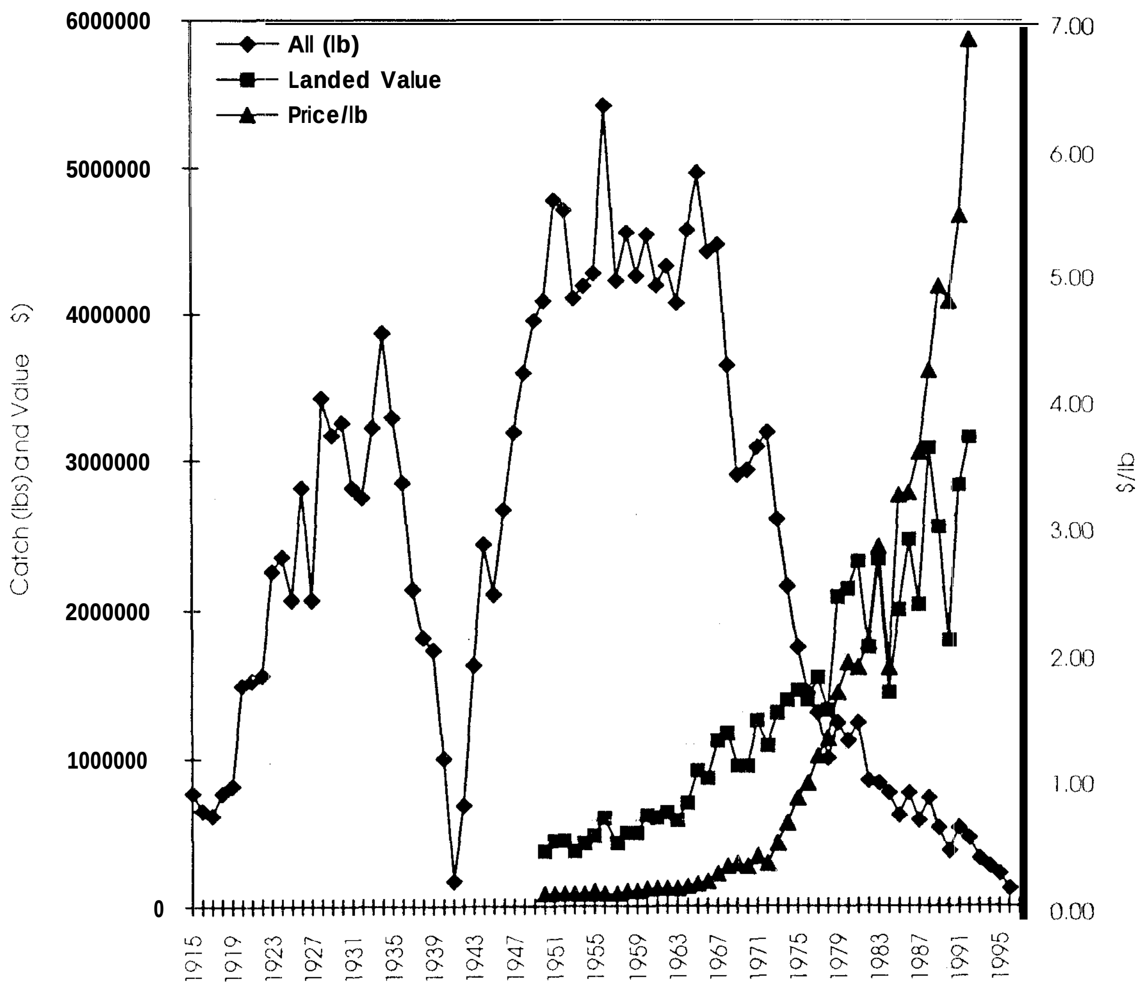


Figure 13. Ex-vessel value of abalone species from California commercial landings, 1972-1993. Data from CDFG.

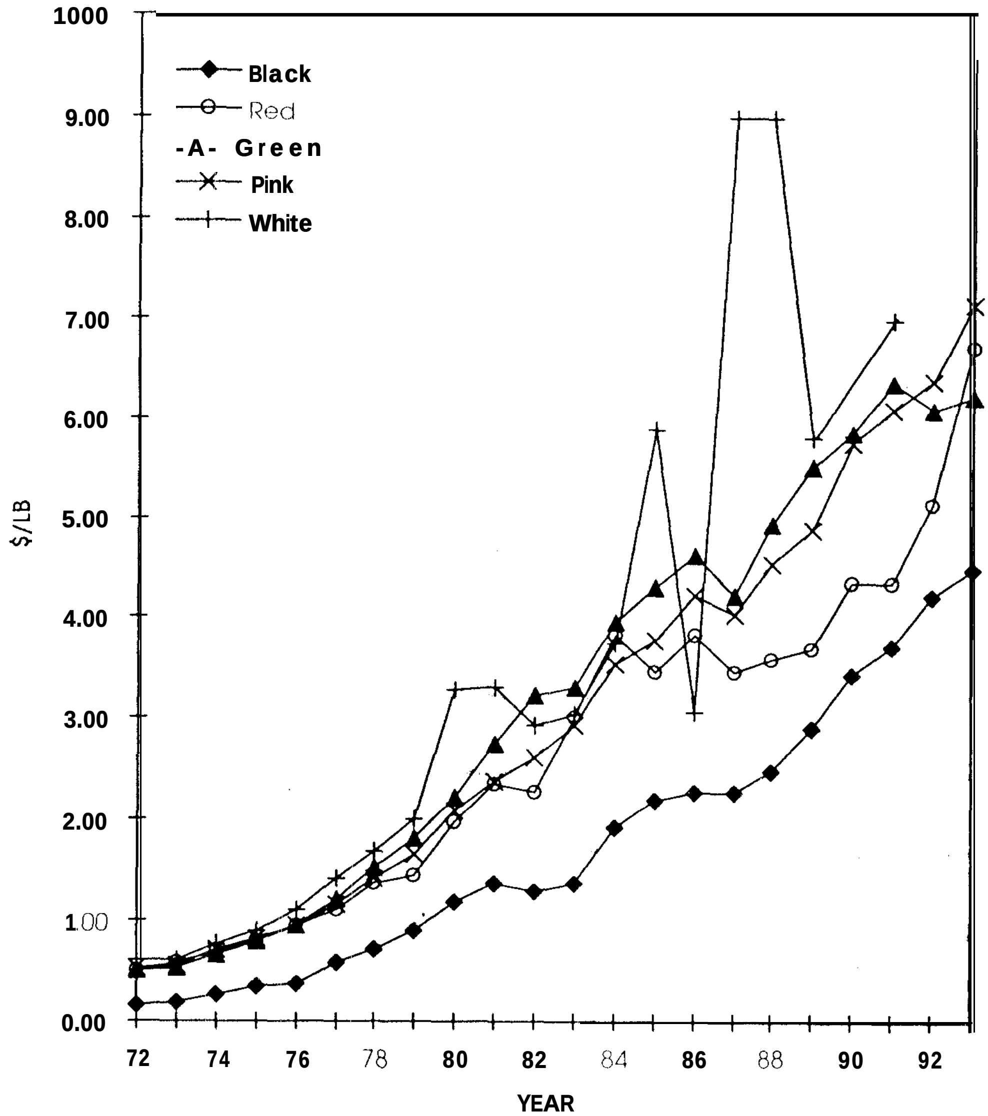
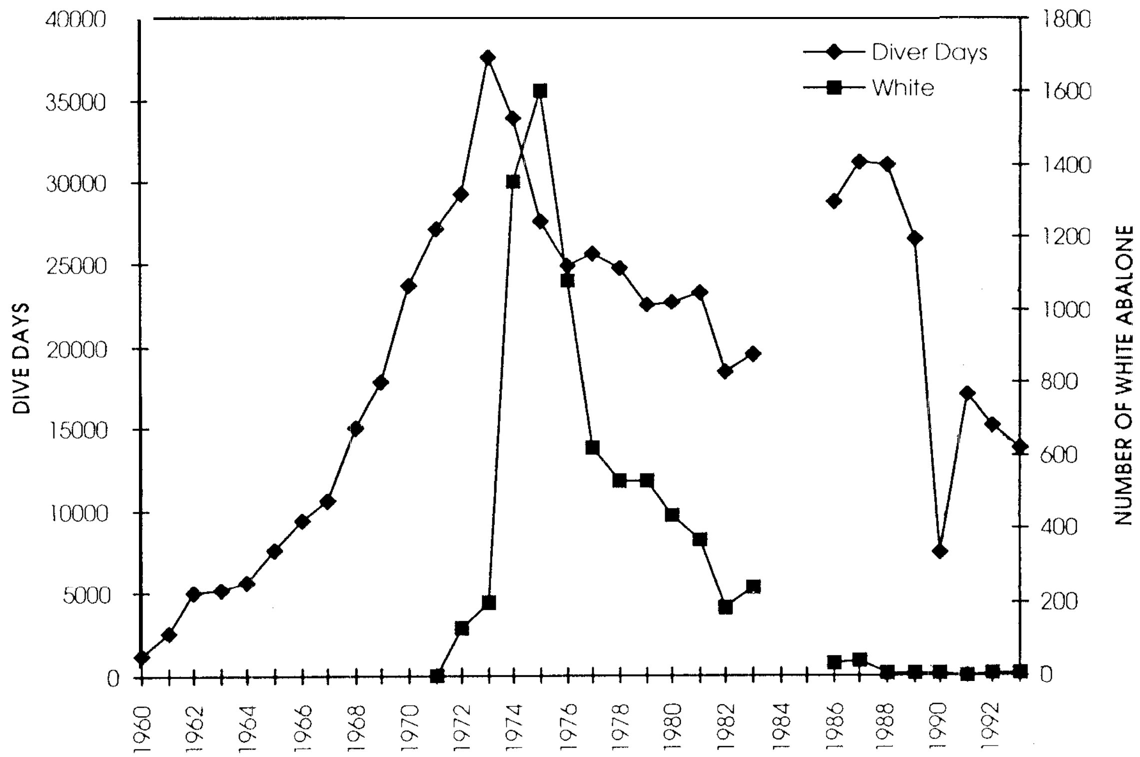


Figure 14. California recreational diver white abalone harvest on California commercial passenger dive boats (CPDB's). A. Numbers of white abalone collected by recreational divers. Not all abalone collected were identified to species. The number of diver days is also shown, as a rough measure of effort. **B.** Recreational diver CPUE on California CPDB's. CPUE is the total number of abalone collected in a year, divided by the number of diver days. No corrections for actual search effort by divers, the effect of closed seasons, or bag restrictions have been made. Data are missing for the period 1984- 1985. Data from CDFG.



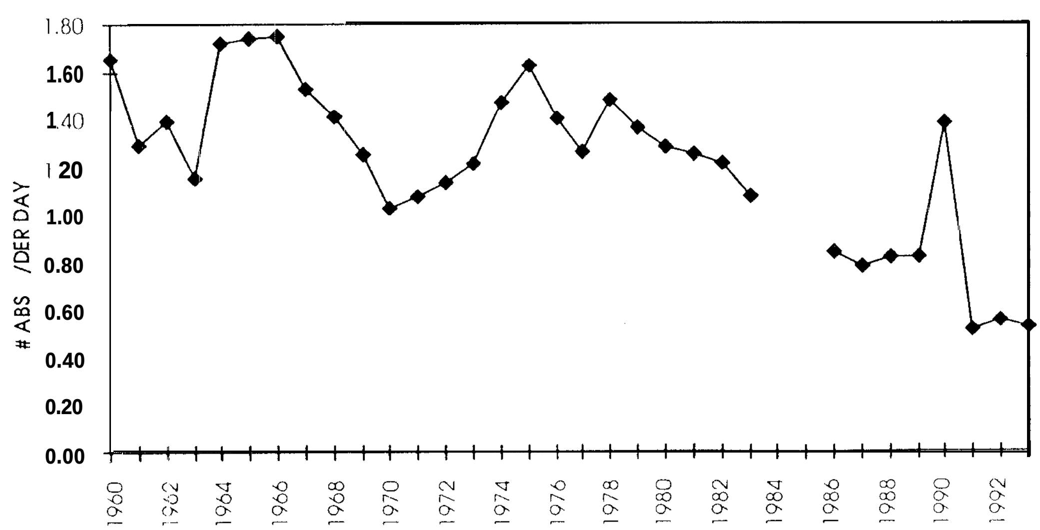


Figure 15. Recreational abalone landings (number) by species from California commercial passenger dive boats (CPDB's). The sharp decreases in 1989 arc due to a reduction in the bag limit (see text). UI is unidentified abalone. Data are missing for the period 1984-1985. Data from CDFC.

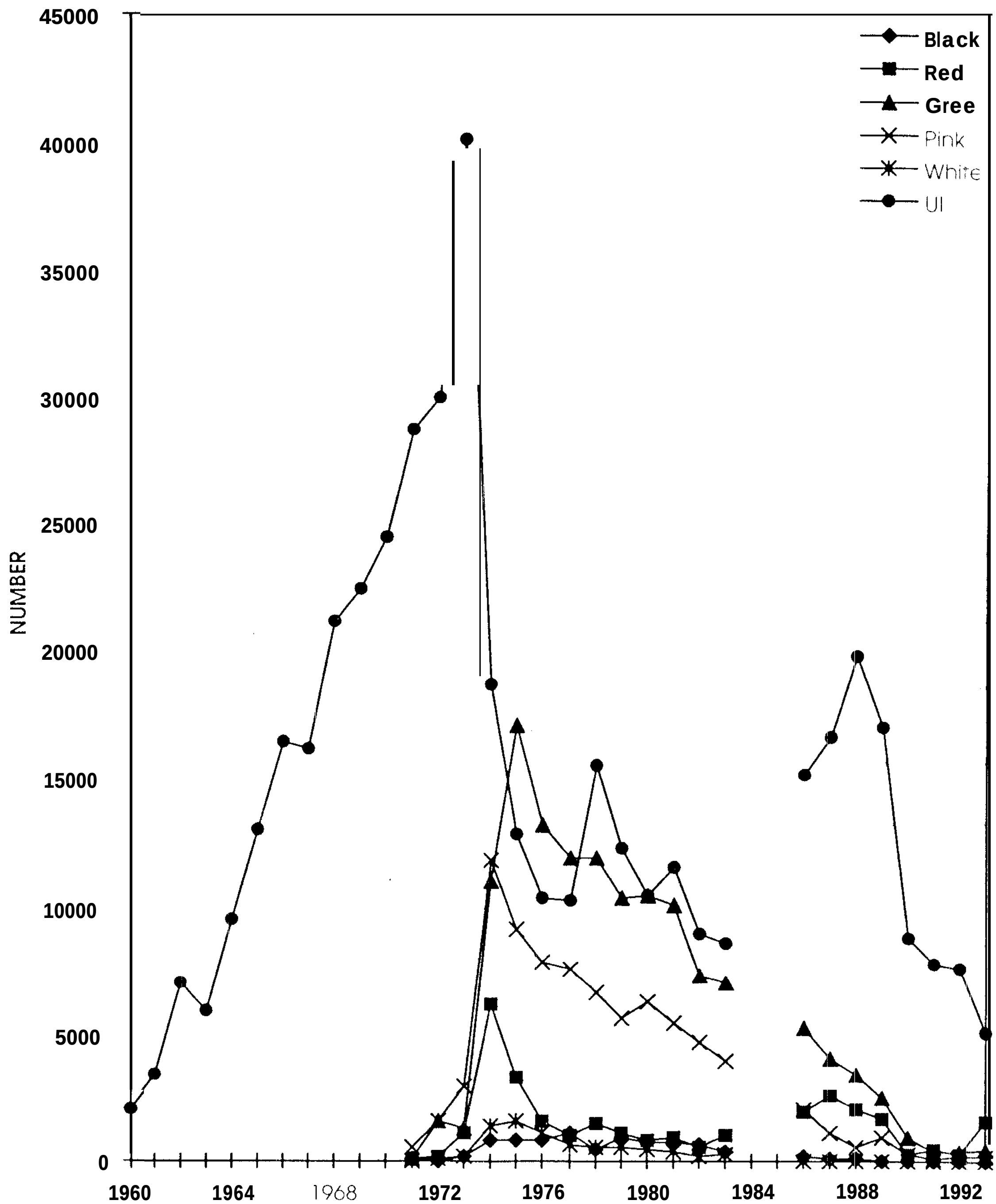


Figure 16. Recreational abalone landings (numbers of animals) by divers on California commercial passenger dive boats (CPDB's) between 1960 and 1993. Abalone were identified to species only after 1971, and then only 45% of abalone were identified to species. The species percentage composition of the total harvest is the upper number at the top of each column, while the lower number is the species percentage composition of the identified catch. Data from CDFG.

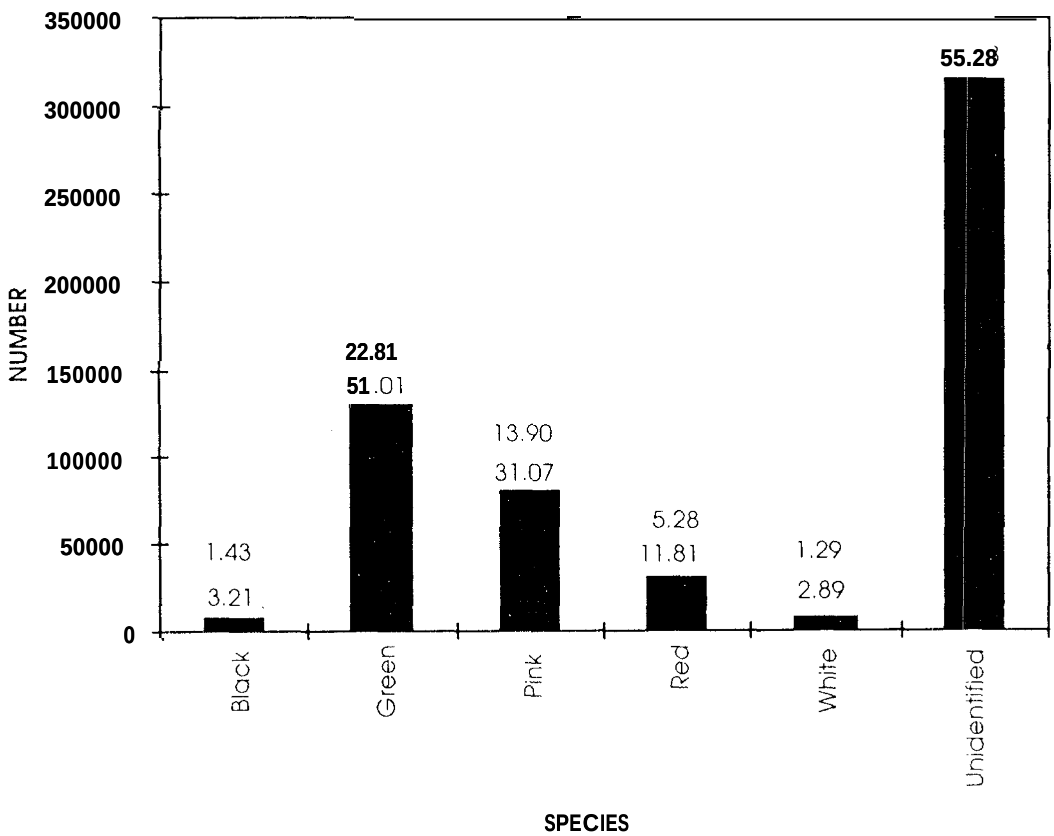


Figure 17. Mexican commercial landings (meat weight) of all abalone species 1940- 1998. Data from 1990- 1998 are for only the four northern--most cooperatives of Zone 1, which landed over 90% of the total Baja California harvest in that. period (Julio Palleiro, Pesca Ensenada, personal communication). Data from Guzman del Proo (1992) and Julio Palleiro, Pesca Ensenada. Location of Zone 1 is shown in **Figure** 2, and the cooperatives are listed in Table **10.**

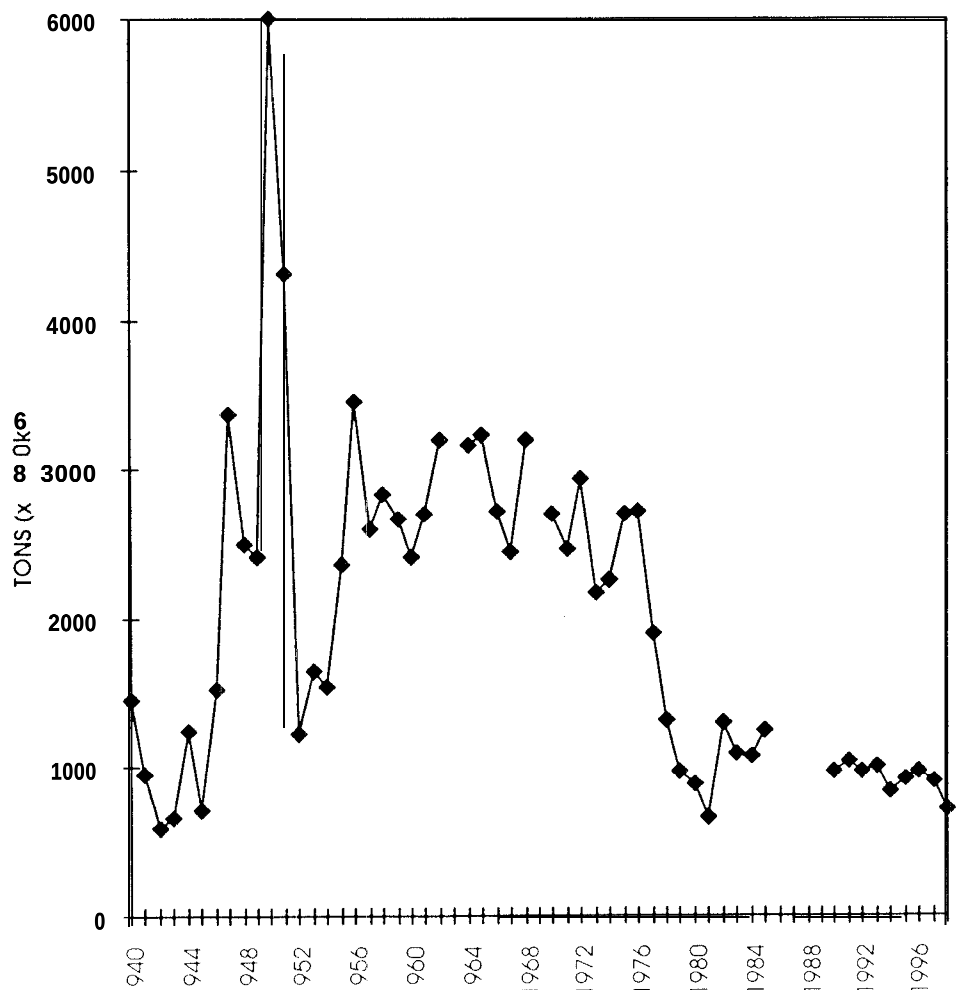


Figure 18. Mexican commercial abalone catch composition (meat weight) for the four northern most cooperatives in Zone 1, 1990- 1997. The percentage of the total catch is given above each species column. Data from Julio Palleiro, Pesca Ensenada.

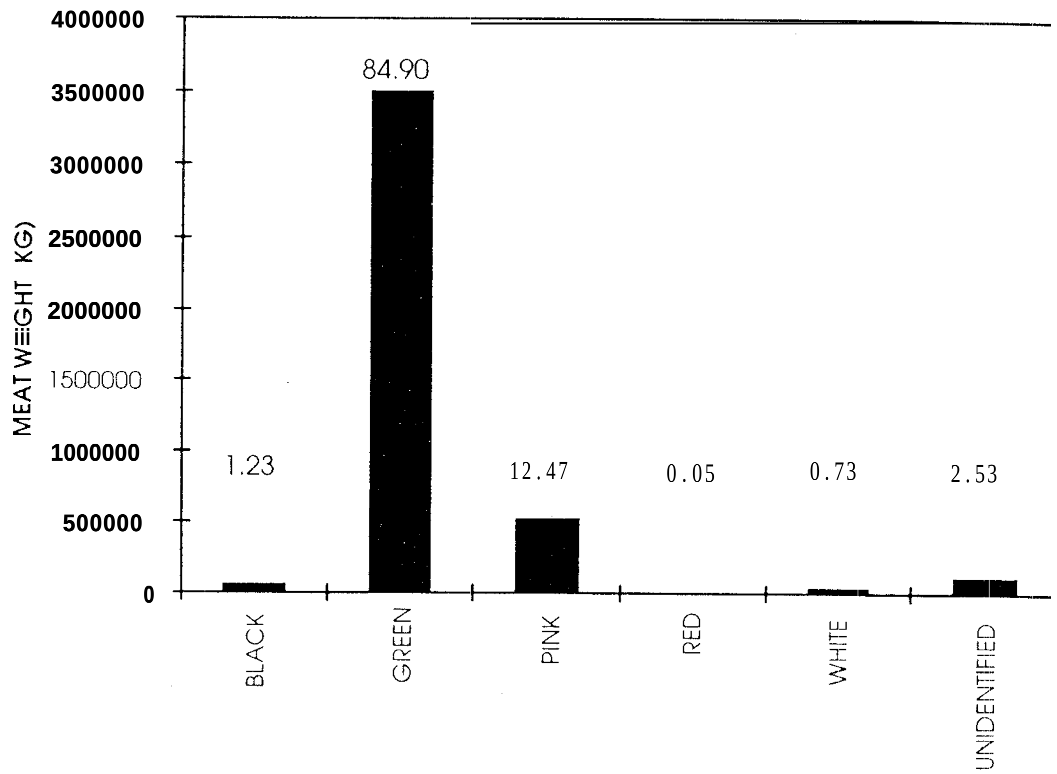


Figure 19. Commercial catch (meat weight) of abalone in Mexico, Zone 1, from 1990-1998. A. All species harvested. B. Same data as A, but with an expanded scale for the four least abundant taxa. Data from Julio Palleiro, Pesca Ensenada

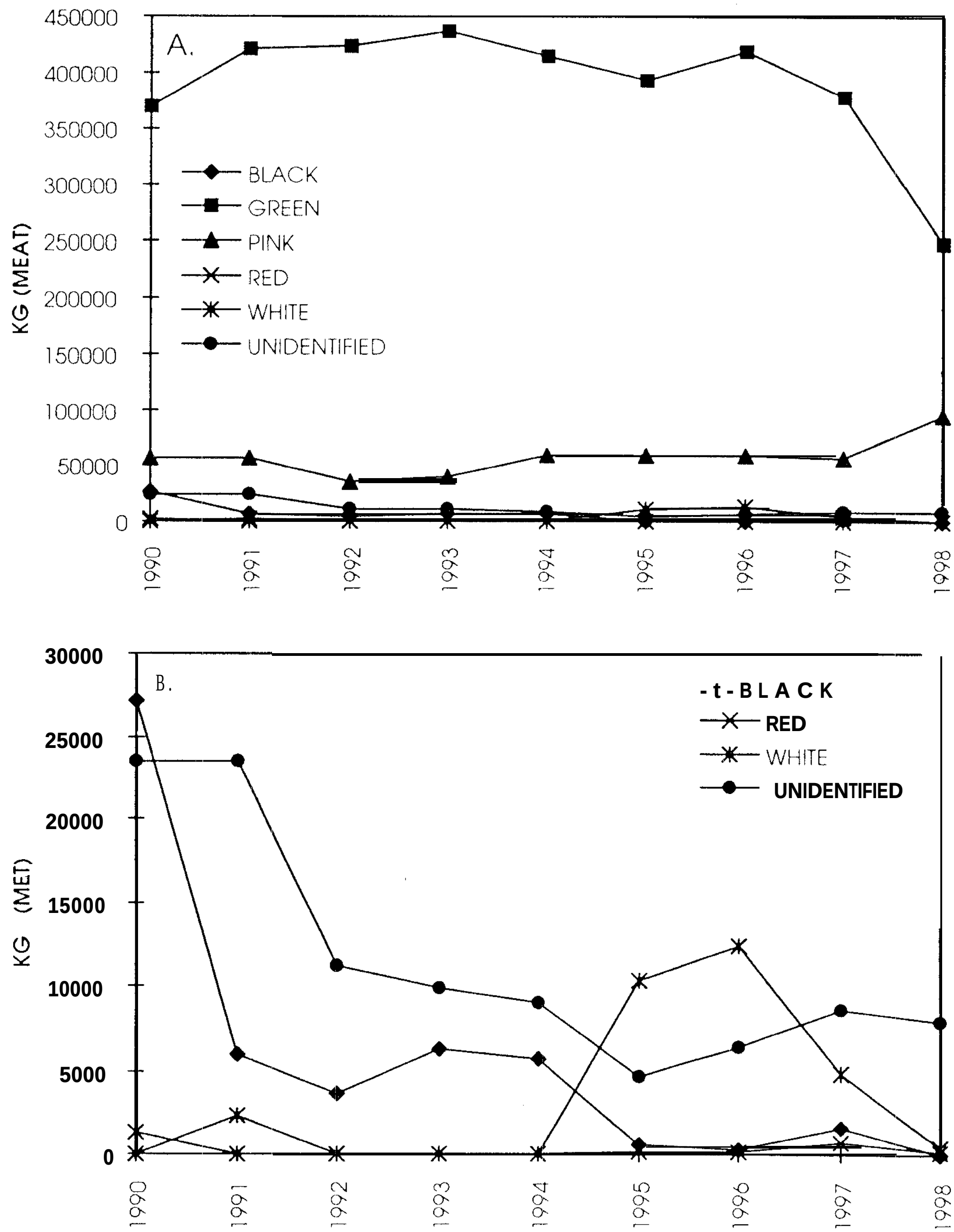


Figure 20. Mexican commercial abalone landings for the four Zone I cooperatives,, 1990- 1998. A. Percent of the Mexican commercial catch by month, all species. **B.** White abalone only; note the change in scale on the y axis. Percent white abalone catch by month and the percentage of the total catch. Note that there is no apparent change in the particular species targeted, nor seasonal serial depletion as the season progresses. Data from Julio Palleiro, Pesca Insenada.

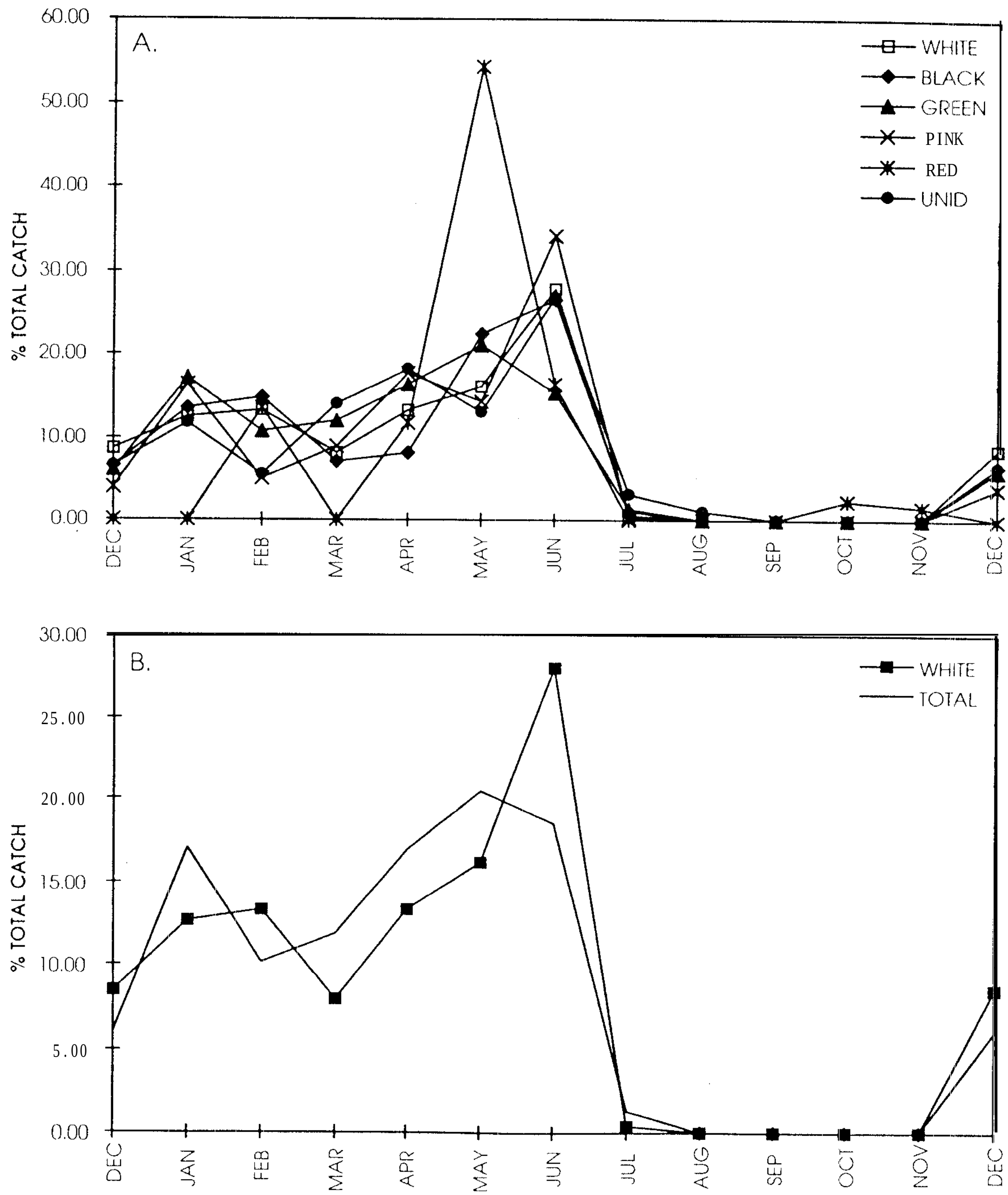


Figure 21. Comparison of the commercial catch by percent occurrence for California and Mexico for the period where species data are available in both countries, 1990- 1998. The methods of reporting catch differ in each county, and so absolute numbers cannot be accurately compared. Data from CDFG and Julio Palleiro, Pesca Ensenada.

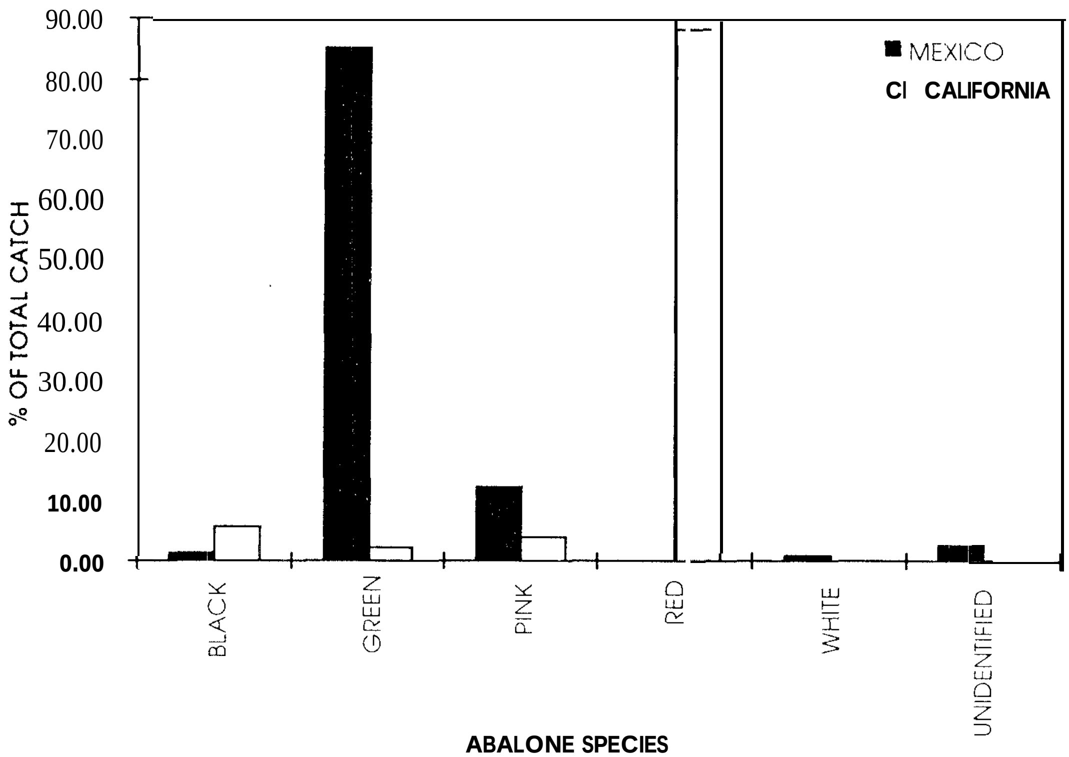


Table 1. West coast abalone species: range, depth and habitat.

Species (yr described)	Common name (Mexican *name)*	Range'	Depth (m) [2]	Habitat[2]
H. sorenseni 1940	White (chino, chinese)	Point Conception-Punta Abreojos[3]	20-60. Also reports from 10 m	below Macrocystis forests.
H. walallensis 1900	Flat	British Columbia to La Jolla, rare south of Carmel.	5-20. Submerges in the southern part of range	kelp forests
H. kamtschatkana 1845	Pinto	Sitka, Alaska-Point Conception	0- 10. Submerges in the southern part of range.	coralline algae and kelp forests
H. k. assimilis" 1878	Threaded. Subspecies of H. *kamtschatkana* [4]	Point Conception-Bahia Tortugas, along the mainland coast	Also a deep water species	common on open rock surfaces
H. rufescens 1822	Red (red, rojo)	Sunset Bay, OR to Bahia Tortugas, Point Eugenia.	O-20. Submerges in the southern part of range, maximum depth goes from 20 to 32 m.	coralline algae and kelp forests
H. fulgens 1845	Green (azul, Blue)	Point Conception-Magdelena Bay	O-10	Eisenia beds
H. cracherodii 1817	Black (Negro, black)	Coos Bay, Oregon-Cape San Lucas, BC	O-5	intertidal
H. corrugata 1828	Pink (amarillo, yellow)	Point Conception-Punta Abreojos	5-20 (or to 40)	Kelp forests.

1. Cox, 1960
2. Lindberg, 1992. Table 1.3
3. Davis et al. 1996
4. Owen et al, 1971.

"H. assimilis is a subspecies of H. kamtschatkana in Owen et al. (1971), H. k. assimilis.

Table 2. Fishery independent surveys and densities of white abalone, H. sorenseni, in California and Mexico. Only emergent abalone were counted in these surveys. References to data are listed below the table.

Date	Location and depth	Density (m^2) (mean ± SE)	Ref.
California			
1972	Catalina Island (20-33 m)	0.23 ± 0.29	1
1980-81	Channel Islands (24-30 m)	0.0021± 0.0009	2
1992-93	Channel Islands (24-37 m)	0.0002 ± 0.0005	2
1996-97	Channel Islands (42-84 m)	0.000167 ± 0.0001	3
Mexico			
1969	Zone I	0.0694	4
1970	Zone I	0.1388	4
1969	Zone II	0.109	4
1970	Zone II	0.104	4
1969	Zone. III	0.149	4
1970	Zone. III	0.038	4
1977-78	Zone III	0	4

References to table.

1. Tutschulte, 1976
2. Davis et al., 1996
3. Haaker, 1998.
4. Guzman del Proo, 1992. Table 24.6 (from Guzman del Proo et al., 1976, but the numbers are slightly different in the tables and data presented in that paper).

Table 3. Common names of west coast abalone and current legal sizes of harvest (or last legal minimum size before fishery closed). All sizes are lengths in mm. References to data are listed below the table.

Species	California common name	California commercial size (recreational)	Mexican common name	Mexican size. Zone I, II, III, IV sizes listed by zone'
H. rufescens	red	197 (178)	red (rojo)	165, 165, 165, 16.5
H. fulgens	green	178[5] (152) [3]	blue (azul)	150, 145, 140, 120
H. corrugata	pink	159 (152) [3]	yellow (amarillo)	140, 135, 130, 110
H. sorenseni	white	159[4] (153[4], 152 [3,5])	Chinese (chino)	140, 135, 130, 110
H. cracherodii	black	146 (127) [5]	black (negro)	120, 120, 120, 120
H. k. assimilis	threaded	102 (102)[3]	striped (rayado)	no size regulation.,
H. walallensis	flat	102 (102)[3,5]		not found in Mexico
H. kamtschatkana	pinto	102 (102)[3,5]		not found in Mexico

1. Leon and Muncino, 1996.
2. Mateus, 1986.
3. http://usafishing.com/shells.html#anchor303633
4. Davis et al., 1996.
5. Tegner, 1989.

Table 4. Regions surveyed and location of live white abalone and empty white abalone shells found in the 1980-1981 and 1992-93 diving surveys discussed in Davis et. al., 1996. Adapted from their Table 1 and **2. Differences:** Their Table 2 for the 1992-93 surveys shows only 14 locations, 27,000 m^2 surveyed and 116 shells found, while their text correctly mentions 15 locations, 30,600 m^2 surveyed and 119 shells found (Davis,pers. comm).

General Location	Specific Location	Date	Depth (m)	Area (m^2)	Live	Shells
Santa Cruz Is.	Yellowbanks	19-Jun-81	27	1,000	3	-
	Yellowbanks	22-Jul-81	29	1,000	3	-
	33°60'N, 119°31'W	6-Apr-92	29-34	3,000	0	26
	33°60'N, 119°31'W	10-Jun-92	30-34	2,500	1	25
	33°59'N, 119°31'W	27-Jan-93	26	4,000	0	2
	33°59'N, 119°32'W	27-Jan-93	30	2,000	0	0
	33°59'N, 119°32'W	27-Jan-93	23-24	4,000	0	0
Anacapa Is.	Cat Rock	14-Aug-80	24	1,000	3	
	Northeast Anacapa	6-Oct-80	24	1,000	2	-
	South Frenchy's	3-Nov-80	28	1,000	2	-
	South Frenchy's	23-Apr-81	26	1,000	1	-
	South Frenchy's	23-Apr-81	25	1,000	2	-
	West End of Island	9-Jul-81	30	1,000	2	-
	Jack Ass Hole	22-Jul-81	24	1,000	2	-
	34°01'N, 119°23'W	6-Apr-92	30	600	0	4
	34°00'N, 119°23'W	10- Jun-92	34-35	1,300	0	5
	34°03'N, 119°22'W	5-Sep-93	33	700	0	12
	34°02'N, 119°30'W	5-Sep-93	26	900	0	18
	34°00'N, 119°23'W	28-Oct-93	26-35	600	0	7
Santa Barbara Is.	7/10 Rock	5-Apr-81	24	1,000	1	-
San Clemente Is.	32°53'N, 118°32'W	3-Dec-93	27	6,000	0	0
Santa Catalina Is.	33°28'N, 118°30'W	13-Dec-93	31-33	1,000	2	13
	33°28'N, 118°30'W	14-Dec-93	31	500	0	1
	33°28'N, 118°30'W	14-Dec-93	31	500	0	3
Total (1980-81)	10 locations			10,000	21	n/a
Total (1992-93)	14 locations			27,600	3	116

Table 5. White abalone noted during diving surveys in California. Modified from Davis et al., (1996). Two invertebrate monitoring programs ran between 1966- 1987 (Channel Islands Research Project, CIRP, J. M. Engle) and 1980-1994 (Channel Islands National Park staff, CHIS), as well as occasional surveys by California Department of Fish and Game, CDFG (R. N. Lea). White abalone were not in the regularly censused animals but 'were noted when seen. These sightings should be considered as "white abalone present at these locations".

Location	White abalone seen?	Years white abalone (not) reported[1]	Survey Program
San Miguel Is.	Never	(1978- 1993)	CIRP, CHIS
Santa Rosa Is.	Never	(1978-1993)	CIRP, CHIS
Santa Cruz Is.			
Gull Island	Yes	1980, 1981, 1986	CHIS
Yellowbanks	Yes	1980, 1981, 1992	CHIS
Anacapa Is.			
Admirals Reef	Yes	1980, 1981, 1983	CHIS
Cat Rock	Yes	1981	CHIS
East Fish Camp	Yes	1982, 1983	CHIS
San Nicolas Is.			
Northeast Light	Yes	1978	CIRP
East Landing Cove	Yes	1978	CIRP
Santa Barbara. Is.			
Arch Rock	Yes	1978	CIRP
Cat Canyon	Yes	1987	CHIS
Landing Cove	Yes	1978	CIRP
Shag Rock	Yes	1978	CIRP
Southeast sea lion rookery	Yes	1978	CIRP
Santa Catalina Is.			
Farnsworth Bank	Yes	1973, 1979	CIRP
Little Harbor	Yes	1966, 1967	CIRP
Ship Rock	Yes	1990	CDFG
San Clemente Is.	Never	(1978- 1986)	CIRP
Los Coronados Is.			
5-minute kelp	Yes	1987	CIRP
Palos Verdes Peninsula	Never	(1978-1986)	CIRP

[1] Years in parentheses indicate the period surveys were conducted if they differ from the period associated with the surveys noted in the Table legend.

Table 6. Summary of white abalone habitat surveys in the submersible Delta 1996-1997 at the California Channel Islands. Dive number indicates the location for Figure 4 (Modified from Table 1 of Davis et al., 1998).

Date	Location	Depth (m)	Area Surveyed (m^2).	Dive #	White abalone found
Anacapa Island					
3 Nov 96	34°00.383'N 119°26.439W	46-6 1	5200	3945	0
3 Nov 96	33°59.926'N 119°22.150W	31-61	2850	3946	0
3 Nov 96	33°59.994'N 119°23.241W	43	4300	3947	2
3 Nov 96	33°59.826'N 119°25.113W	39-43	5300	3948	0
4 Nov 96	34'00.28 1 'N 119°26.408W	43-47	4800	3949	1
6 Nov 96	34°00.615'N 119°24.462W	31-67	2800	3957	0
6 Nov 96	34°00.885'N 119°26.954W	37-49	2750	3958	0
6 Nov 96	34°00.383'N 119°26.439W	31-48	2200	3959	0
Santa Cruz Island					
4 Nov 96	34°01.954'N 119°30.558W	43-46	2550	3950	0
4 Nov 96	33°59.229'N 119°31.316W	44-56	4100	3951	0
4 Nov 96	33°59.029'N 119'33.78 1W	37-66	2150	3952	0
5 Nov 96	33°56.681'N 119°49.736W	33-61	3000	3953	0
5 Nov 96	33°56.810'N 119°46.057W	31-61	700	3954	0
5 Nov 96	33°57.037'N 119°43.021W	49	4000	3955	0
5 Nov 96	34°00.135'N 119°30.556W	49	3650	3956	2
Santa Barbara Island and Osbom Bank					
19 Oct97	33°21.562'N 119°02.458W	47-67	4050	4250	0
19 Oct 97	33°27.906'N 119°03.127W	35-44	1450	425 1	0
19 Oct 97	33°29.594'N 119°04.057W	35-47	3675	4252	1
19 Oct 97	33°30.459'N 119°02.998W	44-60	3000	4253	0
19 Oct 97	33°29.982'N 119°00.034W	45-56	350	42.54	0
20 Oct 97	33°27.575'N 119°02.167W	37-60	4150	4255	0
20 Oct 97	33°27.408'N 119°02.146W	31-50	2400	4256	1
20 Oct 97	33°29.652'N 119°00.942W	32-52	4875	42.57	2
20 Oct 97	33°29.901'N 119°03.754W	51-62	2750	4258	0
Total	24		77,050		

Table 7. Estimated total area of white abalone habitat (rocky reef 25-65 m depth) within the species historic range from Point Conception to Puma Eugenia. The potential white abalone habitat was calculated as the portion of the bottom with rocky substratum between the 25-65 meter contours, estimated at 3%. (Modified from Davis et al., 1998, Table 2).

Location	Shelf length at the 25-65 m depth contour (km)	Mean shelf width (km)	Total shelf area (ha)	Potential white abalone habitat (ha)
Point Conception to Santa Barbara	75	0.5	3750	112
San Miguel Is.	34	0.3	1020	31
Santa Rosa Is.	61	0.4	2440	73
Santa Cruz Is.	40	0.3	1200	36
Anacapa Is.	34	0.2	680	20
San Nicolas Is.	42	0.3	1260	38
Santa Barbara Is. and Osborn Bank	57	0.3	1710	52
Santa Catalina and Farnsworth Bank	90	0.4	3600	108
San Clemente Is.	33	0.4	1320	40
Tanner and Cortez Banks, Bishop Rock	177	0.5	8020	242
Islas Los Coronados	17	0.2	340	10
Islas de Todos Santos	21	0.4	840	25
San Martin	19	0.4	760	23
Cedros Is.	70	0.4	2800	84
Punta Eugenia	60	0.4	2400	72
Total	830		32140	966

Table 8. Commercial catch of white abalone by location in California for the period 1958-1997. No data are available for 1975. Prior to 1959 the reported catch of white abalone was zero. The percentage of the catch at each location as a portion of the total catch at the known locations is provided at the end of each location column. The percentage of the total white abalone catch that was taken in each year is listed for each location. The maximum percentage catch for each location is listed at the bottom of the table. Note that catch was concentrated in a few years at each location.

		Anacapa Is		Santa Cruz Is		Santa Rosa Is		San Miguel Is		Santa Barbara Is		Santa Catalina Is		San Nicolas Is		San Clemente Is		Tanner and Cortez Banks, Bishop Rock		Point Conception to Point Dume		Point Dume to Palos Verdes		Palos Verdes to Mexico		Unknow
Year	Total (Lbs)	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt	%	Wt
1958	0															0										
1959	5075															5075										
1960	0															0										
1961	1337															1337										
1962	0															0										
1963	0															0										
1964	0															0										
1965	438	0	O W	0	O,X	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	438	0.10	0	0 00	0	0.00	0	0.00	0	O W	0
1966	0	0	0.00	0	O W	0	0.00	0	0 00	0	0.00	0	0.00	0	0.00	0	0 00	0	0 00	0	0.00	0	0.00	0	O W	0
1967	4100	0	0.00	0	0.00	0	0,00	0	0.00	0	0.00	0	0.00	0	0.00	4100	0 9T	0	0.00	0	0.00	0	0.00	0	0.00	0
1968	845	0	0.00	0	O,X	0	0.00	0	0.00	0	0.00	0	0.00	0	O,X	845	0 zo	0	0.00	0	0.00	0	0.00	0	0.00	0
I969	ZT3dT	0	0.00	0	0.00	0	0.00	0	O,M	I9SO	23.50	1848	47.99	1105	96.25	16779	3.96	5503	8.08	0	O,X	150	3.54	12	0.I6	0
1970	10954	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	168	4.36	0	0.00	4591	1.08	6195	9.10	0	0.00	0	0.00	0	O W	0
1971	36152	402	6.54	0	0.00	0	0.00	0	0.00	I06	1.28	0	0 00	0	0.00	28686	6.76	5142	7.55	0	0.00	0	0.00	I8I6	24 36	0
1972	143076	0	0.00	3	0.80	128	29.22	12	4.90	542	6-S3	0	0.00	0	0.00	121485	28.64	I9880	29.19	12	0.79	163	xes	851	11.42	0
I9T3	81205	821	13.35	50	13.40	242	55 25	159	64.90	802	9.66	387	10.05	0	0.00	74136	17 48	3138	4.61	48	3.15	15	0.35	1407	18.87	0
1974	110648	940	15.28	132	35.39	0	0.00	28	11.43	2338	28.17	3O3	7.87	0	0.00	96MZ	22.63	7843	11.52	93	6.10	1036	24.47	1733	23.25	200
1975	71250																									
1976	80615	2345	38.12	3O	8.04	Z	0.46	25	10.20	2038	24.56	3TZ	9.66	0	0.00	54045	12.74	19456	28.57	364	23.88	1407	33.23	371	4.98	160
1977	15055	1415	23.00	S	1.34	49	II.I9	0	0.00	482	5.81	551	14.31	40	3.48	I0869	2.56	375	0.55	56	3.67	978	23.10	235	3.15	0
1978	3645	69	1.12	T	1.88	10	2.28	3	1.22	0	0.00	60	1.56	0	0.00	3334	0.79	0	0.00	93	6.10	3S	0.83	34	0.46	0
1979	soz	0	0.00	111	29.76	Z	0.46	3	1.22	17	0.20	0	0.00	0	O,X	48	0.0I	182	0.27	132	8.66	0	0.00	T	0.09	0
! 980	1051	17	0.28	9	2.41	0	0.00	3	I.22	0	0.00	20	0.52	0	O W	651	0.15	0	0.00	T	0.46	0	0.00	342	4.59	2
1981	109	0	0.00	e	2.14	0	0 00	0	0.00	0	0.00	0	0.00	0	0.00	16	0.00	17	0.02	9	0.59	0	0.00	59	0.79	0
1982	902	I9	0.31	9	2.41	0	0 00	0	0.00	0	0.00	0	0.00	0	0.00	IT3	0.04	376	0.55	3Z	2.10	0	0.00	293	3.93	0
1983	480	33	0.54	Z	O,K	0	0.00	0	0 00	0	0.00	0	0.00	0	0.00	157	0.04	0	0 00	T3	4.79	0	0.00	155	2.08	60
1984	449	90	1.46	T	I 88	5	1.14	12	4.90	0	0.00	6S	1.61	0	0.00	143	0.03	0	0.00	31	2.03	0	0.00	28	0.38	TI
1985	1541	0	0.00	0	0.00	0	0.00	0	0.00	17	0.20	0	0.00	3	0.26	I00I	0.24	0	000	10	0.66	450	10.63	60	0.80	0
1986	876	0	0.00	0	0.00	0	0.00	0	0.00	5	0.06	TO	1.82	0	0.00	229	0.05	0	0.00	544	35.69	0	0.00	ze	O T	0
1987	Z	0	0.00	0	O W	0	0.00	0	0 00	Z	0.02	0	0.00	0	0.00	0	0.00	0	0 00	0	O,M	0	0.00	0	0.00	0
1988	Z	0	0.00	0	0.00	0	0 00	0	0 00	0	0.00	0	0.00	0	0.00	0	0 00	0	0 00	0	0.00	0	0.00	z	0.03	0
1989	22	0	0 X	0	0.00	0	0.00	0	0 00	0	0.00	0	0 00	0	0.00	0	0.00	0	0 00	0	0.00	0	0.00	22	0.3O	0
I990	17	0	0.00	0	0.00	0	0.00	0	0 00	0	0.00	0	0 00	0	0.00	17	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
1991	Z	0	0 X	0	0 X	0	0 00	0	0 00	0	0 00	0	0.00	0	0 X	0	000	Z	0 00	0	0.00	0	O,M	0	0.00	0
1992	0	0	O W	U	0.00		0.00	0	0.00	0	0.00	0	0 00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
1993	0	0	0.00	0	O,M	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0
1994	33 4	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	10.02	0.26	0	0.00	23.38	0.01	0	0 00	0	0.00	0	0.00	0	0.00	0
1995	25.05	0	0.00	0	O,X	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	5.01	0.00	0	0.00	20.04	I.31	0	0.00	0	0.00	0
I996	0	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0 00	0	0 00	0	0.00	0	0.00	0	0.00	0
1997	0	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	U	0 00	0	0.00	0	0.00	0	0.00	0	0.00	0
Total (lbs) by area	526505	1.17		OOT		0.08		0.05		1.58		0.73		0.22		80.57		12.94		0.29		0.80		1.42		0.09
Total (lbs)	597755	6151		373		438		245		8299		3851 02		1148		424186		68109		1524.04		4234		7455		493
Max %	43.10		38.12		35.39		55.25		64.90		28.17		47.987		96.254		28 64		29.189		35.695		33.23		24 36	

Table 9. Price per pound (ex-vessel) for the five commercially harvested California abalone species between 19'72 and 1.993. The price is for animals in the shell. Data from CDFG. No white abalone were harvested in 1990, and 1992-1993.

Year	Black	Red	Green	Pink	White
1972	0.17	0.5 1	0.5 1	0.52	0.60
1973	0.18	0.58	0.54	0.56	0.62
1974	0.26	0.69	0.67	0.7 1	0.77
1975	0.33	0.78	0.80	0.8'2	0.90
1976	0.37	0.95	0.95	0.95	1.12
1977	0.59	1.11	1.22	1.1'7	1.42
197s	0.7 1	1.36	I.54	1.44	1.69
1979	0.9'1	1.46	1.83	1.65	2.00
1980	1.18	I.98	2.23	2.09	3.28
1981	1.37	2.35	2.73	2.38	3.29
1982	1.30	2.26	3.22	2.62	2.92
1983	1.36	3.02	3.30	2.92	3.05
1984	1.94	3.8 1	3.96	3.54	3.75
1985	2.19	3.45	4.29	3.77	5.88
1986	2.28	3.82	4.61	4.2 II	3.07
1987	2.28	3.46	4.22	4.04	9.00
1988	2.47	3.59	4.93	4.53	9.00
1989	2.90	3.68	5.52	4.89	5.80
1990	3.42	4.36	5.86	5.75	
1991	3.72	4.36	6.36	6.09	7.00
1992	4.23	5.14	6.1 1	6.40	
1993	4.49	6.73	6.22	7.141	

Table 10. Location of the abalone fishing cooperatives in Baja California. Zones and cooperatives currently existing are listed from north to south. Data from Leon and Mucino (1996). Earlier sources may show five zones (e.g. Guzman del Proo, 1992). The placement of cooperatives into the zones is also somewhat variable depending on the source. For example, Pescadores Nacionales de Abulon is sometimes in Zone II. Zone locations are shown in Figure 2. The number of cooperatives fishing for abalone also varies depending on the time and source. The number of the cooperatives shown here are used to reference the cooperative in later tables.

Zo	Location	#	Cooperative	Operations Base
]	Border to 28" N.	1	Abuloneros y Langosteros	Guadalupe Is.
		2	Ensenada (took over the re. of Noroeste coop)	Border to Bahia del Rosario
		3	Rafael Ortega Cruz	Bahia de Santa Ros
		4	Pescadores Nacionales de Abulon	Cedros Is.
1	28°N to 27°09 N (de Punta Malarrimo to Bahia Asuncion)	5	Buzos y Pescadures de la E California	Natividad
		6	La Purisima	Point Eugenia
		7	Bahia Tortugas	Bahia Tortugas
		8	California de San Ignacio	San Ignacio
I]	Bahia Asuncion -Punta Malcc San Ignacio Lagoon	9	Leyes de Reforma	
		10	Progress0	
		11	Punta Abreojos	Pun ta Abreojos
I'	Punta Malcomb, San Ignacio Lagoon -El Conejo	12	Cadejo	
		13	Puerto Chale	
		14	Pescadorcs de La Poza	
		15	Bahia Magdalena	

Table 11. Total number of white abalone observed by zone during the surveys of Guzman del Proo et al. (1976). The number of abalone found in their Zone I and II are combined to match the current zone system, as shown in Figure 2. The number of 14.4 m^2 quadrats surveyed each year is also shown. Data modified from Table A2 of Guzman del Proo et al., 1976. Densities calculated from these quadrats do not match tlhose given in the text of this document and Guzman del Proo et al., 1976, which are ecological densities!, densities of abalone in suitable habitat. These quadrat data are shown to indicate the scale of the survey. Note that white abalone were only found in Zone I and II.

Year	Zone 1	Zone II	Zone III	Zone IV	# quadrats	Total white abalone
1968	1	0	0	0	162	1
1969	9	14	0	0	1074	23
1970	7	4	0	0	1080	11
Total	17	18	0	0	2321	35

Table 12. Mexican abalone fishing season by zone. All species are harvested during the fishing season. Data from Leon and Muncino (1996).

Zone	Abalone Season
I	1 December - 30 June
II	3 1 December - 3 1 July
III	31 December - 31 July
Iv	1 February - 31 August

Table 13. Percentage of the total abalone catch made up by white abalone in three months in Baja California. during 1973, by zone. The percentage of the white abalone catch that was harvested below the legal size is also provided. The legal size in 1973 was not given in the source, but was probably 135 mm. Data from Lluch Belda et al., 1973.

	May		June		July		Average
	%	% illegal	%	% illegal	%	% illegal	
Zone 1	7.7	26.1	54.07	28.64	56.54	23.03-	39.43
Zone 2	5.4	34.4	0.17	0	0.01	0	1.136
Zone 3	0.6	30.1	2.0	31.2	33.8	98.8	36.4
Zone 4	0.0	-	0.0	-	0.0		0.0

Table 14. Commercial harvest of white abalone (% total catch) in Mexico. Modified from data in Guzman del Proo (1992, Table 24.5). Note that the regions listed do not correspond to the zones shown in **Figure 2** of this report, which follow the scheme of the: most recent, publication (Leon and Muncino, 1996).

Year	Ensenada to Santa Rosalita	Cedros Is. to Natividad Is	Punta Eugenia to Punta Prieta	South of Punta Prieta
1968		3		**0**
1969	0	13	0	**0**
1970	27	20	3	**0**
1973		2		
1974		2		
1975		3		**0**
1976		0	0	**0**
1984		0.5		

Table 15. Percent catch composition for the Mexican commercial fishery in '1973, by month. Data from Quintanilla and Aceves (1976, Table 4). Note that white abalone were only a large fraction harvested during the first month of the 1973 season.

	Pink	Green	White	Black
January	67.46	15.49	17.04	
February	64.22	29.53	1.72	4.52
March	77.34	22.47	0.18	
April	70.59	28.7	0.09	0.61
May	70.58	27.48	1.72	0.20
June	56.30	41.09	1.37	1.22

Table 16. The percentage catch by species for five cooperatives in Zones I and II from the 1992/93 and 1993/94 seasons. Data modified and recorded from Murueta et al. (1996). Data were from shell analyses made a few weeks after the catch was processed for each season and then pooled for both seasons. The names of the five cooperatives au-e listed in **Table 10.** The total amount of meat harvested is shown in **Table 17.** Cooperative 2* (number 3 in original table of Murueta et al. (1996)) has since merged with Cooperative 2 of **Table 10.** The threaded abalone is not reported to occur in the Mexican commercial harvest: in any other sources, and may have been confused with the white abalone; both lack a muscle scar.

Cooperative	Green	Pink	Red	White	Threaded	Black
1	most	next most				some
2	6.0	21.8	2.5	65.1		4.5
2*	29.7	4.8		0.1		65.4
4	74.0	24.3	-			1.7
5			93.3		6.7	

Table 17. Effort and catch in the 1992193 and 1993/94 abalone fishing seasons for the five cooperatives in Zones I and II (cooperative numbers correspond to those: given in **Table 10).** Cooperative 2* (number 3 in original table) has since merged with Cooperative **2** of **Table 10.** DNF (Did not fish abalone). A "-" indicates that no data were available. The catch is kilograms of meat (abalone removed from the shell), and was not divided into species data. Data from Murueta et al. (1996).

	1992-93				1993-94			
Cooperative	Teams	Trips	Catch (kg)	CPUE (kg/trip)	Teams	Trips	Catch (kg)	CPUE (kg/trip)
1	7	344	5,099	14.8	7	241	4,159	17.26 -
2	20	-	15,476		20	-	10,825	
2*	DNF	-	0		8	105	97.2	9.26
4	22	1607	198,384	123	22	1523	198,366	103.25
5	15	-	8,726		15	1197	14,659	12.25
Total	64	227,	685		72		228,981	----

Table 18. Mexican commercial catch (weight of meat) from Zone 1 between 1990 and 1998. Data from Julio Palleiro, Pesca Ensenada.

Year	Black	Green	Pink	Red	White	Unidentified	Total
1990	27119	369859	56010	1291	0	23503	477782
1991	5921	421077	56977	6	2363	23450	517742
1992	3603	423114	34536	0	0	11215	484775
1993	6198	436945	38184	37	0	9816	495968
1994	5589	415011	59563	7	0	8965	411498
1995	529	393949	59234	76	10311	4695	458903
1996	357	418952	59011	100	12307	6410	484830
1997	1600	378111	55734	717	4788	8604	444766
1998	0	247754	95584	182	420	7812	351332
Total (kg)	50916	3504772	514833	2416	30189	104470	4127596
% Total	1.23	84.91	12.47	0.059	0.73	2.53101321	

Table 19. Comparison of the percentage catch composition from the period 1990-1998 from the California and Mexican (Zone 1) abalone fisheries. In this period the catch is reported differently, and so percent occurrence is the best comparison. Data from Julio Palleiro, Pesca Ensenada, and CDFG.

Species	Black	Green	Pink	Red	White	Unidentified
Mexico	1.23	84.9 1	12.47	0.06	0.73	2.53
California	5.61	2.10	3.78	88.44	0.00	0.06

Table 20. Size (mm) at maturity, (minimum and 50%) of abalone in each Mexican management zone. Minimum size at maturity is the smallest size at which mature individuals are found. The 50% size at maturity is the size at which 50% of the sampled individuals are mature. This size generally varies between studies, and each size given here represents the finding of a different study. It is likely that both the sizes at maturity vary between local populations, from year to year depending on conditions, or with the method used to find the size at maturity. Modified from Leon and Muncino (1996).

	Zone 1		Zone 2		Zone 3		Zone: 4	
Species	Min.	50%	Min.	50%	Min.	50%	Min.	50%
White	-	-	-	-	-	133	-	-
Red	-	150	-	-	-			
		169						
		170						
Black	106	124	-	-	-	119	-	-
						120		
						126		
Green	95	145	96	105	110	125	62	101
		148		145		129		116
				148		147		117
				152				122
								127
Pink	90	129	92	121	65	132	60	110
		130		135		132		120
				138				