Serial depletion and the collapse of the California abalone (*Haliotis* spp.) fishery

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Abstract: Failure to manage the California abalone (*Haliotis* spp.) fishery as individual species, using spatially discrete fishing grounds and temporally discrete fishing periods, contributed to poor management decisions, ultimately leading to the 1997 closure of both the commercial fishery statewide and the southern recreational fishery. Here we examined patterns in the decline of abalone landings from 1942 to 1996 by species, catch area, and fishery period (years). There were four distinct phases in the fishery characterized by landings that increased, were apparently stable, rapidly declined, and gradually declined prior to closure. The apparently sustainable period (1952–1968) occurred as declining landings of pink abalone were replaced by increased take of red abalone. This was followed by a dramatic serial depletion of successive species during the depletion period (1969–1982). In the red, pink, and black abalone catch there was sequential spatial depletion of mainland fishing grounds, followed by smaller or nearby islands, and then finally depletion of the larger offshore islands. Fisheries independent stock survey assessments confirmed that the reduced landings resulted from population depletions. Life history differences among the species suggested that black, green, and white abalone were more vulnerable to overutilization and may be less likely to recover than red abalone. Increases in catch per unit effort and market value confounded management in the final period (1983–1996), hindering efforts to close the fishery of each abalone species until major stock declines had already occurred.

Résumé : Le fait de ne pas gérer séparément la pêche des différentes espèces d'ormeau (*Haliotis* spp.) de Californie, en établissant des aires de pêche distinctes et des périodes de pêche distinctes, a contribué à la prise de mauvaises décisions de gestion, ce qui s'est traduit finalement par la fermeture, en 1997, de la pêche commerciale dans l'ensemble de l'État et de la pêche sportive dans la partie sud. Dans le présent document, nous étudions les profils de la baisse des débarquements d'ormeau, de 1942 à 1996, par espèce, par zone de capture et par période de pêche (années). Nous avons observé quatre phases distinctes dans la pêche, à savoir : une augmentation des débarquements, une stabilité apparente des débarquements, une baisse rapide des débarquements puis une baisse progressive précédant la fermeture. La stabilité apparente (1952–1968) correspond à la période où la diminution des débarquements d'ormeau rose a été compensée par une augmentation des captures d'ormeau rouge. Cette période a été suivie d'une série spectaculaire d'effondrements des espèces, les unes après les autres, pendant la phase de baisse rapide (1969–1982). Dans le cas de la récolte des ormeaux rouges, roses et noirs, nous avons observé un épuisement séquentiel sur le plan spatial : d'abord les aires de pêche de la partie continentale, puis celles des petites îles ou des îles avoisinantes, et finalement celles des grandes îles du large. Les évaluations des stocks effectuées indépendamment du secteur de la pêche ont confirmé que la réduction des débarquements était attribuable à un affaiblissement des populations. D'après les différences du cycle vital des diverses espèces, il semble que les ormeaux noirs, verts, et blancs seraient plus vulnérables à une surexploitation, et que la probabilité de leur rétablissement serait plus faible que celle des ormeaux rouges. L'augmentation des prises par unité d'effort et de la valeur marchande ont désorganisé la gestion dans la dernière période (1983–1996), entravant les tentatives de fermeture de la pêche de chacune des espèces d'ormeau jusqu'au moment où on n'a pu que constater de graves baisses des stocks.

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Introduction

The abalone (*Haliotis* spp.) fishery in California south of San Francisco has suffered dramatic declines over the past several decades, resulting in closure of the commercial and recreational fishery in 1997. The collapse of this major fishery, which landed more than 2000 metric tons during the 1950s and 1960s, occurred despite fishery management efforts. Today, in northern California, red abalone (*H. rufescens*) stocks continue to be abundant north of San Francisco due to important differ-

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ences in management between the two regions (Tegner et al. 1992). The two major differences were prohibiting recreational use of SCUBA and excluding commercial take of abalone from the north (Cox 1962; Karpov and Tegner 1992; Tegner et al. 1992).

Historically, abalone have been the basis for important fisheries along the west coast of North America beginning with early aboriginal settlers (Cox 1962). Closures, however, occurred early in the commercial abalone fishery in California. During the last century, the commercial green (*H. fulgens*) and black (*H. cracherodii*) abalone fishery in the littoral zone reached its peak in 1879 (Cox 1962; Cicin-Sain et al. 1977) and by 1913 this fishery was closed (Cox 1962; Edwards 1913). More recently, in the 1980s, the once-favored white abalone, *H. sorenseni*, was fished to unsustainable levels, giving *H. sorenseni* the dubious distinction of being one of the few marine species fished to near extinction (Tegner et al. 1996; Davis et al. 1998). The commercial abalone closure was a tragedy for the divers who lost their livelihoods, the public whose natural heritage was lost, and resource managers whose fishery management efforts failed. In hindsight, the declines in the fishery might have been more easily recognized if fishery managers had examined the fishery data, taking into account individual species within the fishery as well as the spatial complexity of the stocks.

In this study, we examine abalone catch statistics from 1942 to 1996 for evidence of serial (sequential) depletion by species and by area. We separate the time series into four major fishery periods. The California abalone complex includes five major species: red, pink (*H. corrugata*), green, black, and white abalone. We examine landing trends by species and catch by area. Catch records are analyzed for patterns in spatial serial depletion at mainland, nearby island, and distant island fishing grounds. We corroborate the trends in the fishery statistics with fishery independent survey data to confirm the magnitude of the stock declines, focusing on the most recent periods of decline. We discuss additional factors, which may have contributed to management failures in this fishery, including reliance on catch per unit effort (CPUE) data, increases in abalone value, and a lack of resolve and funding for management. Finally, we examine suggestions for more conservative management which, if adopted, could help prevent future abalone fishery collapses.

Methods

Fisheries dependent and independent data were utilized in this study. Fisheries dependent data were based on landings reported by abalone divers on mandatory landing receipts. These landing data included the number of abalone landed, their value in US dollars, and location of catch by Fish and Game statistical block numbers spanning 10 minutes of latitude and longitude. Numbers of abalone landed were converted to weight using a fixed average value specific to each of the five species (Oliphant 1979).

We assigned landed weight for all five species to catch locations, i.e., specific segments of the coast and islands, based on the block number of the catch location for data from 1950 to 1996. We divided the area from San Francisco to Mexico into three areas: northern (San Francisco to Año Nuevo including the Farallon Islands), central (Año Nuevo to Point Conception, the sea otter range), and southern California (south of Point Conception) (Fig. 1). Southern California was further subdivided into three coastal segments, eight islands, and a set of combined banks. Only red abalone were fished commercially north of Point Conception. Percent of peak catch (1950–1996) by species was determined at each of the 14 locations to compare magnitude of catch declines. Our graphical analysis of area-specific catch examined locations that represent over 95% of the cumulative catch for a species.

Fisheries independent data included timed swim counts and density surveys. Timed swim counts, initiated in 1973, were used to provide an index of abundance for red, pink, and green abalone. Swims were conducted using SCUBA on appropriate habitat at the Channel Islands during 1973, 1974, 1976, 1983, and 1993–1998. Counts were depth stratified by expected species distribution in southern California, i.e., pink and red abalone from 6 to 24 m and green abalone from 3 to 6 m (Cox 1962; Tutschulte 1976).

Density surveys for red and pink abalone were noninvasive counts on 60 m^2 transects from 16 Channel Islands National Park (CINP) stations. These surveys were conducted on five northern CINP Islands, which have been surveyed annually since 1983 (Davis 1989). The methods used in our analysis of red abalone were described in Karpov et al. (1998). Here we expanded our analysis to include pink abalone at six locations on Santa Cruz Island (4), Santa Barbara Island (1), and Anacapa Island (1). Black abalone density survey data were collected on permanent intertidal quadrats at 11 locations at San Miguel Island (3), Santa Rosa Island (5), Anacapa Island (2), and Santa Barbara Island (1). At each location five quadrats from 1 to 60 m^2 were examined each year without destroying habitat or injuring abalone. Censuses were conducted during low-tide periods in the late summer and winter from 1985 through 1999.

The ex-vessel value of abalone in dollars per kilogram was computed for combined species from 1950 through 1996. Values were standardized to 1995 US dollars using the yearly Consumer Price Index for southern California. After 1982, landing data included sufficient information to calculate value by species, value of catch in dollar per vessel day, and CPUE in kilograms per diver days.

Results

Landing periods (1942–1996)

The trends in total commercial landings of abalone during 1942–1996 exhibited four stages (Fig. 2). Period A (1942–1951) was characterized by increasing landings. Period B (1952–1968) reflected apparent stability in landings. During period C (1969–1982) landings declined relatively rapidly. Finally, period D (1983–1996) reflects a gradual, but steady decline that ended in complete fishery closure in 1997.

Landings of a species complex

The patterns observed in the combined landings mask patterns of the individual species landings (Fig. 2). During period A, red abalone landings increased rapidly during the last years of World War II (1942–1945) followed by a gradual

Fig. 1. Location map of California, showing northern, central, and southern commercial abalone take areas and the range of the sea otter through 1997.

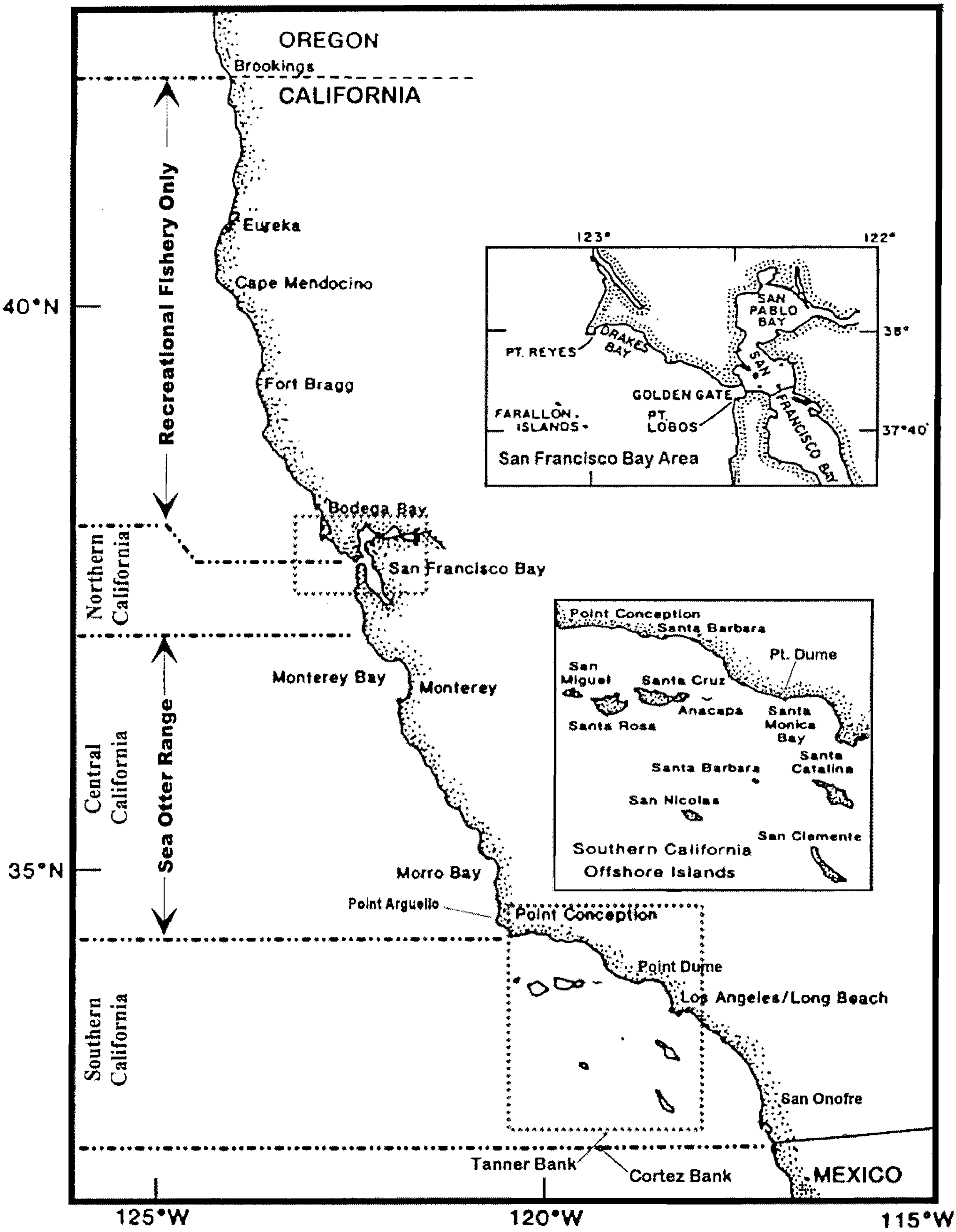
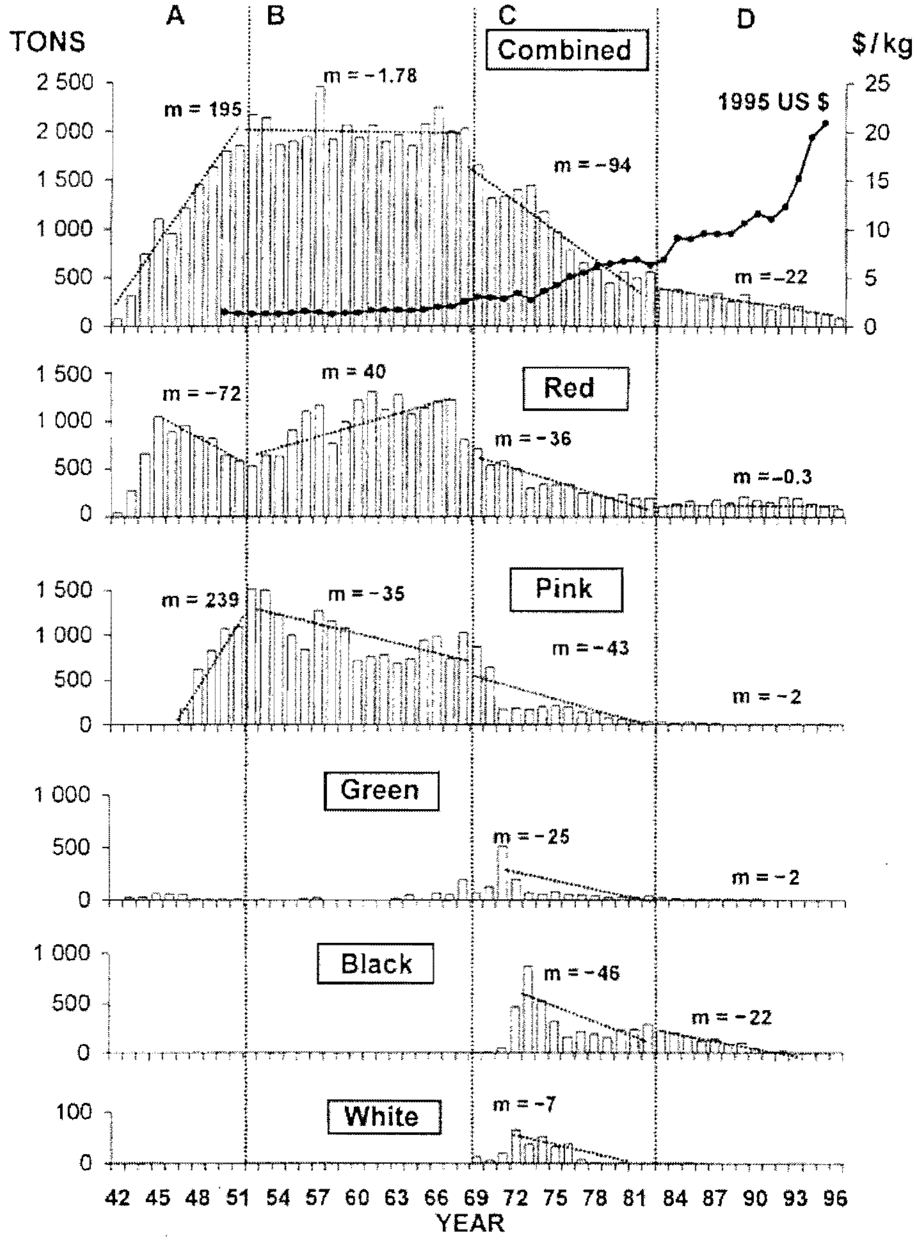


Fig. 2. Commercial landings (metric tons) of California abalone fishery (bars), combined (top), and by red, pink, green, black, and white abalone. Landings are divided into periods (A–D) by trends in the total fishery landings, with regression lines (dotted lines) for each period. (m = slope, $t \cdot year^{-1}$). Regressions are provided for individual species where sufficient data exists. The average annual value of all species (US$ per kilogram) is represented by a solid line.



decline to 1951. Combined landings continued to increase to the end of the period as pink abalone entered the fishery from 1947 to 1951. The pink abalone fishery began after red abalone landings peaked and began to fall. The only other abalone landed during period A, green abalone, contributed little to the overall landings.

Period B was not one of stability for the component species. Red abalone landings gradually increased until 1967 followed by a long decline extending through the next period. Pink abalone landings declined throughout this period to levels lower than red abalone. Toward the end of period B, when both red and pink landings were declining, green abalone landings increased supplementing the cumulative landings.

Period C was a period of steady and rapid decline in red, pink, green, and black abalone landings, each of which declined to levels far lower than historic landing highs. The most dramatic declines of any of the abalone species was that suffered by the white abalone, which declined to 0.6% of the 1972 historic peak by 1982. None of the lesser abundant three species achieved the tonnage or apparent durability of red or pink abalone.

During period D all species, except red abalone, continued to decline until the fishery closure in 1997 (Figs. 2 and 3). Throughout this period red abalone landings appeared stable, but at far lower than historic landing levels. Black abalone were reduced to 2.0% of peak prior to the 1993 closure. The pink, green, and white abalone fisheries ended in 1995 at 0.5, 0.1, and 0.03% of their respective peak landings. During the last year of the fishery (1996), red abalone landings were 87 t, representing a 17% decline from 105 t in 1983, but almost a 90% decline from the historic peak in the early 1960s.

Catch by area and level of decline

Area specific catch from 1950 for red, pink, and black abalone revealed a spatial trend in catch with higher catches coming from mainland or nearshore islands, shifting over time to more remote areas, with catches declining at larger islands before smaller ones. Catches of green and white abalone did not show a spatial pattern in decline, but remained concentrated in a few areas, suggesting these two species were limited in their spatial distribution prior to exploitation. Declines in catch varied by species and area, but in most cases dropped two orders of magnitude from catches in peak years and areas (Table 1).

During period B, most red abalone were caught in central California, followed by southern mainland, Santa Cruz, Santa Rosa, and San Miguel islands (Fig. 4). During this period and into C, catches declined first along the central coast. Catches declined less abruptly along the southern mainland, Santa Rosa, Santa Cruz, and San Nicolas islands. During periods C and D, catches decreased off the three islands to 3, <1, and <1% of their respective peak catch (Table 1). San Miguel Island and the north coast were the exceptions to this pattern. Catches from San Miguel Island, the farthest and most northern of the Channel Islands, and the north coast (District 10) comprised 71 of the 87 t landed in 1996 (30 and 23% of peak catch, respectively) just prior to the fishery closure in 1997.

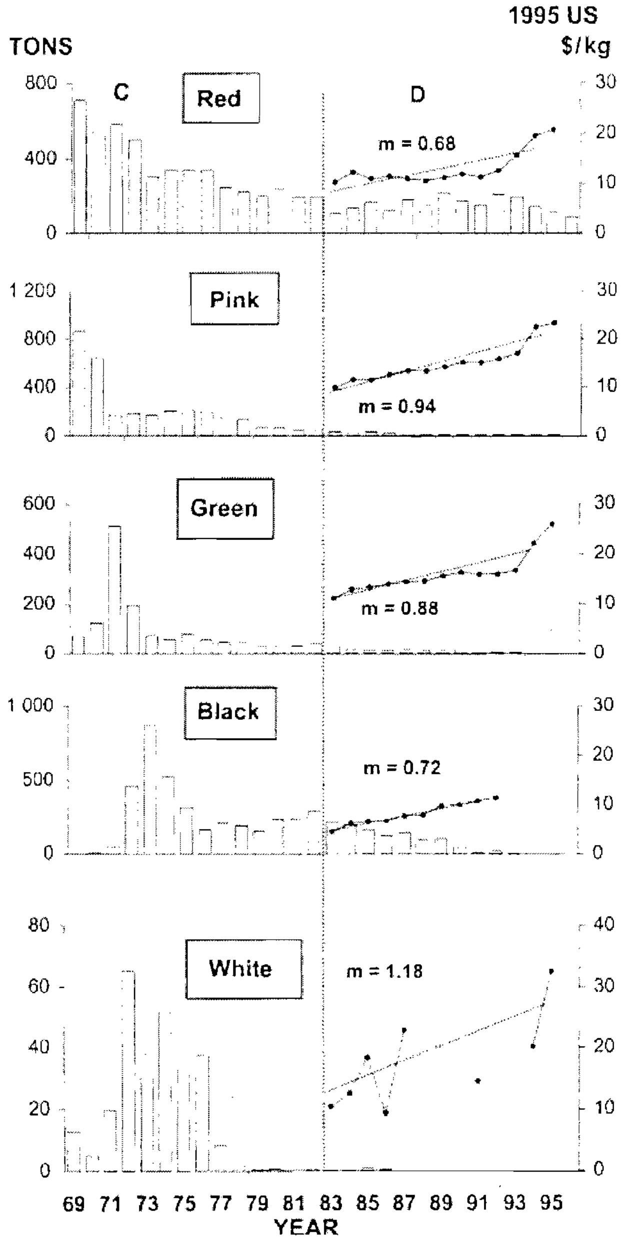
Following a similar pattern, pink abalone catches during period B increased to peak catch first along the mainland, Santa Barbara, San Clemente, and Catalina islands, followed by growth on Santa Cruz and Anacapa islands (Fig. 5). Following this initial growth phase, declines were most abrupt along the mainland and at Santa Barbara Island. During period C, San Clemente and Santa Cruz islands declined. Unlike red abalone, no remnant areas remained to sustain pink abalone landings into the final period D with all areas declining to less than 8% of peak catch (Table 1).

Green abalone catch during period B came primarily from Santa Catalina Island in 1956–1957 then later from the Southern mainland and San Clemente Island (Fig. 6). Declines during period C and into D were most pronounced off San Clemente and mainland areas with remnant catches persisting from Santa Catalina Island.

During period C, black abalone catch developed and peaked at many of the islands in 1973 with catches slowly increasing from the more remote San Nicolas Island in period D (Fig. 7). Declines in black abalone catch were first apparent at Santa Rosa Island in period C. During period D, catch continued to decline with the last landings coming from San Miguel, San Clemente, and San Nicolas islands. Before the fishery closure, catch had fallen to 4% or less of the peak catch for each of the islands (Table 1).

White abalone catch peaked and declined to <1% of the peak catch in just 14 years during period C at each of the areas examined (Table 1, Fig. 8). During period D, the white abalone fishery at each of the five major locations had essentially collapsed.

Fig. 3. Landings for red, pink, green, black, and white abalone, in periods C and D (bars). The ex-vessel average value (solid line), with fitted regression lines (dotted line). (m = slope, $t \cdot year^{-1}$).



Fisheries independent abundance and density data

Abundance (abalone per hour) or density (abalone per hectare) data collected during periods C and D confirmed that population estimates declined in conjunction with catch during the final stages of the abalone fishery. Abundance and density surveys revealed profound declines for most species at the locations surveyed. Many of the abundance and density figures, with few exceptions, showed dramatic declines approaching or reaching densities or counts of 0.

Table 1. Abalone catches taken one year before the fishery closures (1992–1996), expressed as a percent of peak catches that occurred in 1961 for red, 1952 for pink, 1971 for green, 1973 for black, and 1972 for white abalone in California.

	Abalone species				
Location	Red	Pink	Green	Black	White
North coast	30	—	—	—	—
Central coast	<1	—	—	—	—
Southern coast					
Point Conception to Pt. Dume	2	1	<1	—	<1
Pt. Dume to San Onofre	5	<1	<1	—	<1
San Onofre to Mexico	<1	<1	<1	—	<1
Southern islands and banks					
San Miguel Island	23	3	5	2	<1
Santa Rosa Island	3	7	<1	<1	<1
Santa Cruz Island	<1	<1	<1	<1	<1
Anacapa Island	9	<1	<1	<1	<1
San Nicolas Island	<1	6	<1	1	—
Santa Barbara Island	<1	<1	<1	2	<1
Santa Catalina Island	<1	<1	<1	3	<1
San Clemente Island	<1	1	<1	<1	<1
Tanner and Cortez banks	2	<1	<1	—	<1

Note: — Indicates area was not fished for that species.

Red abalone abundance and density trend analyses showed mixed results with declines at Santa Cruz and Santa Rosa islands, but not at San Miguel Island (Fig. 4). Santa Cruz, close to the mainland, had low initial abundance and density estimates that rapidly declined to 0. Santa Rosa Island, further offshore, had higher initial abundance and density estimates that also declined to low levels by the end of the period. At San Miguel Island abundance estimates declined, but density estimates showed no clear decline during period D.

Fishery independent pink abalone surveys yielded zeros in abundance or density at all areas except San Clemente Island by the end of period D (Fig. 5). At Santa Barbara Island densities and abundance estimates were initially low and remained low or at 0 during period D. Values fell to 0 at both Anacapa and Santa Cruz islands during period D. San Clemente Island was the only location where abundance declined but did not reach 0.

As with pink abalone, abundance surveys for green and density surveys for black abalone showed major declines through the final years of the fishery in all areas surveyed (Figs. 6 and 7). Green abalone trends in stock abundance were only monitored on Santa Catalina and San Clemente islands. In both areas final abundance declined by two orders of magnitude to timed swim counts of <1 abalone $\cdot$ h^{-1}.

Intertidal densities of black abalone approached or fell to 0 at all Channel Island locations monitored from 1985 through 1999 (Fig. 7). Densities declined to 0 at the islands close to mainland, first with Anacapa in 1990 and Santa Rosa Island in 1992, followed by declines at San Miguel Island (the farthest from the mainland) in 1995.

Market value, value of vessel landings, and CPUE

Market value of abalone increased at an accelerating rate during periods C through D (Fig. 2). Ex-vessel cost of abalone per kilogram in US dollars, adjusted for inflation to 1995 dollars, rose gradually during period B at \$0.06 $\cdot$ $year^{-1}$. During the two periods of landing decline, the combined value of abalone accelerated. The slope of adjusted cost during periods C and D was 0.37 and \$0.95 $\cdot$ $year^{-1}$, respectively, increasing from \$2.98 in 1969 to \$20.93 by 1995.

Value increased as landings declined during period D (Fig. 3). The value of white abalone, whose landings had essentially collapsed by 1983 at the end of period C, continued to increase at the greatest rate of all species, tripling to \$33.56 between 1983 and 1995. Red abalone, which showed no decline in landings during period D, had the lowest increase in real value of the five species, doubling to \$20.70.

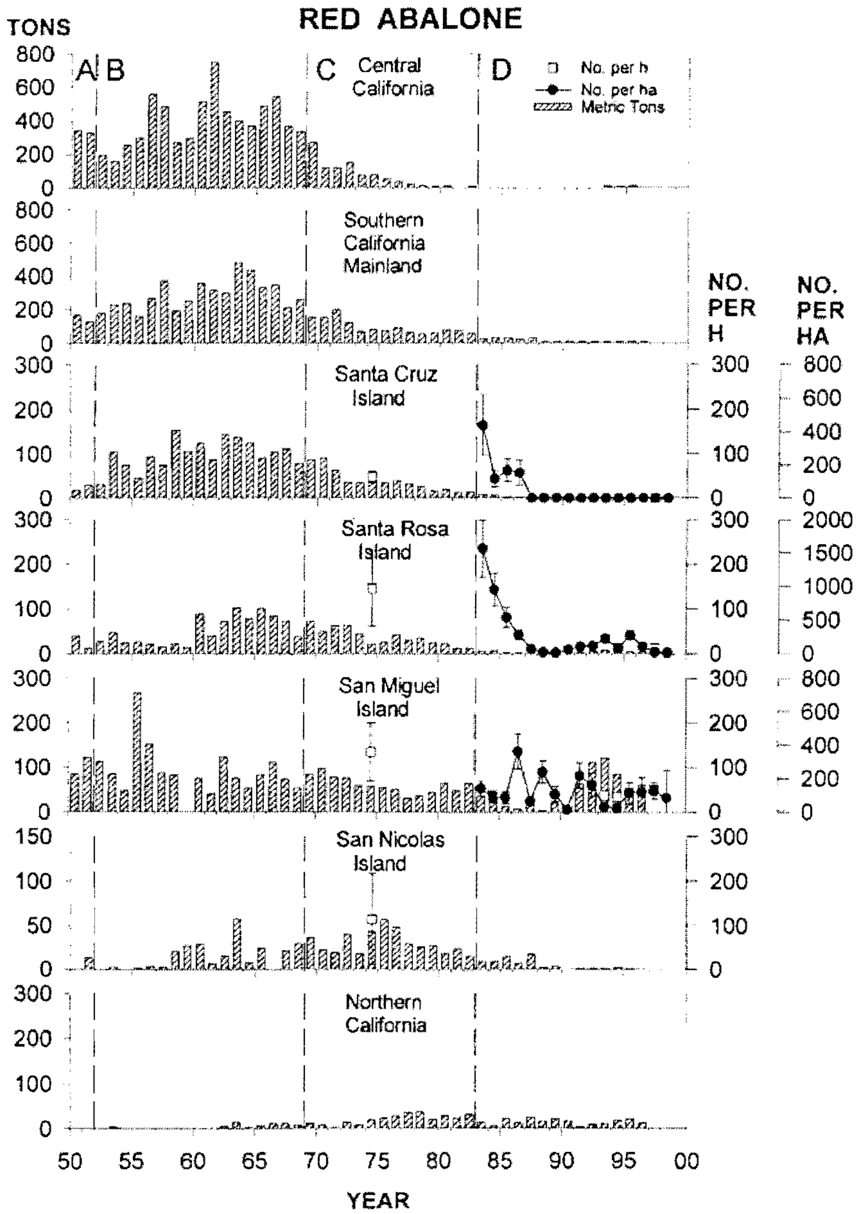
Trends in CPUE did not parallel landings during period D except for red and black abalone (Figs. 2 and 9). Surprisingly, red and pink abalone CPUE was highest in later years. Green abalone CPUE remained essentially level, declining only during the last few years of the fishery in 1994 and 1995. Black abalone CPUE declined slightly while white abalone showed no definitive trend. During this same period, value per boat landing tripled for red and pink abalone, remained level for green and black abalone, and peaked in 1985 for white abalone (Fig. 9).

Discussion

Sustainable fishery?

We found no evidence for sustainable commercial catch in the California abalone fishery at any time during the fishery

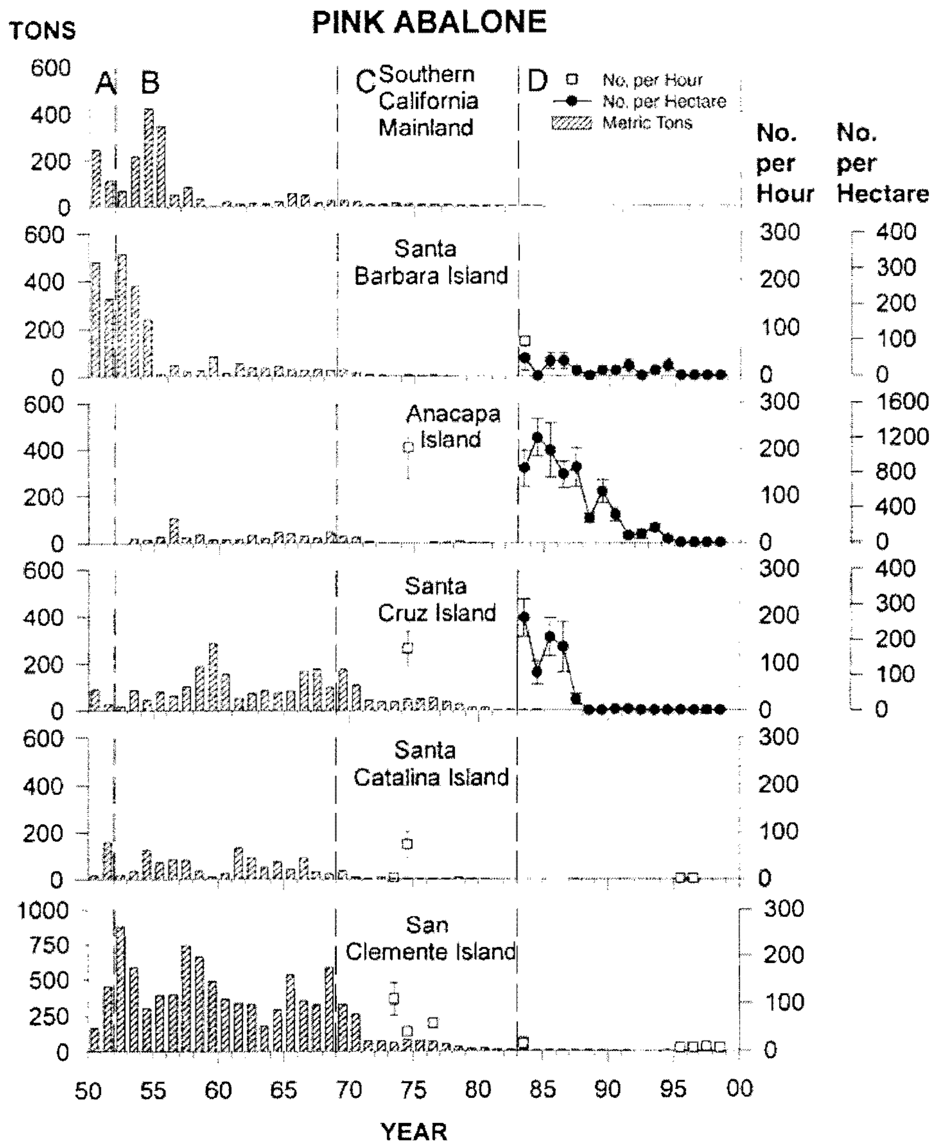
Fig. 4. Red abalone catch (metric tons, bars), density (number per hectare, solid dots), and number per hour (open squares) from northern, central, and southern California mainland, and four Channel Islands. Catch is divided by landing periods. Catch areas are ordered from top to bottom by accessibility to fishery. Vertical lines around points are SE.



(1942–1996). Examination of combined abalone landings revealed four distinct phases in the fishery. There was a building phase (Period A), in which landings steadily increased presumably during the initial exploitation phase of the fishery. Increases in landings can occur as new areas are opened to exploitation in spatially complex fisheries (Orensanz et al. 1998) or as accumulations of old and (or) large individuals are utilized (Francis 1986). As the fishery matured, it appeared to remain stable for almost two decades (Period B), however, combined landings masked the replacement of declining pink abalone with red abalone. The fishery began a period of sharp decline in 1969 (Period C), in which a series of species were sequentially depleted. The reoccupation of central California by the southern sea otter in the 1960s decimated red abalone populations in that area and consequently commercial fishery landings (Wendell 1995). The decline in the combined landings appeared to slow as landings reached low levels (Period D); however, an examination of catch data during this period revealed a pattern of serial depletion by fishing area. Fishery independent data corroborated these declines in the fishing areas.

The one exception to this pattern of dramatic decline has been the recreational fishery for red abalone in northern California. North of San Francisco, abalone may not be taken using SCUBA or surface supplied air. This regulation results in a *de facto* reserve at depths beyond 8.5 m (Karpov et al. 1998). This has resulted in a large-scale spatial harvest refugia for the deeper portions of the population. Walters, as cited in Orensanz et al. (1998), suggested that sustainable fisheries result from spatial accidents which protect a large

Fig. 5. Pink abalone catch (metric tons, bars), density (number per hectare, solid dots), and number per hour (open squares) from southern California mainland, and five Channel Islands. Catch is divided by landing periods. Catch areas are ordered from top to bottom by accessibility to fishery. Vertical lines around points are SE.



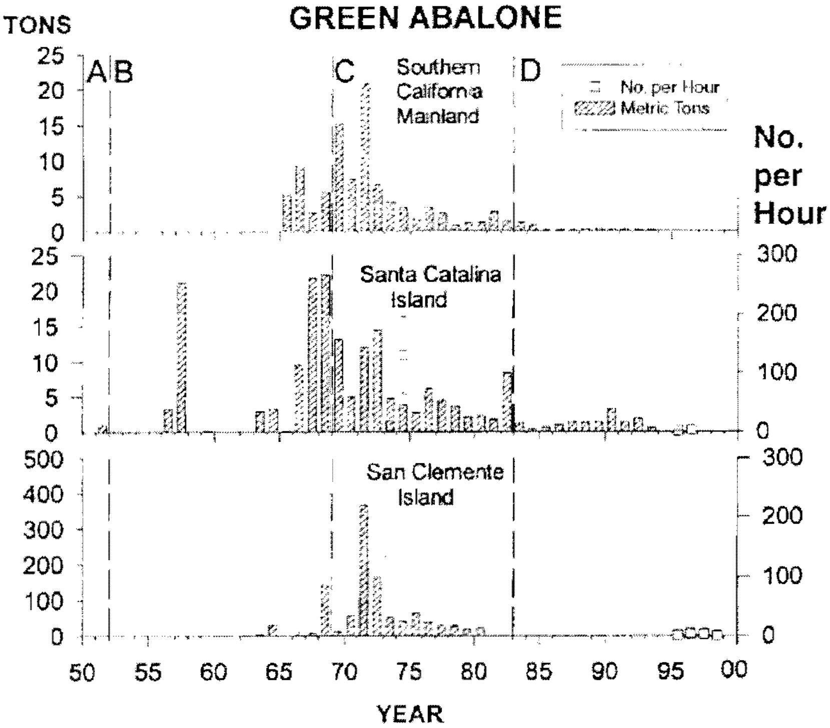
portion of the stock. This may be part of the explanation for the success of the recreational red abalone fishery in northern California. The northern fishery is also less complex to manage with only one species in a geographically simpler area with no offshore islands. Other factors that help protect these stocks include longer periods of inclement weather and large areas of coast inaccessible to recreational divers. Given the levels of decline found in southern California in both fishery-dependent and -independent data, it is perhaps surprising that stronger management action was not taken earlier to protect stocks. What masked the dramatic problems in this fishery?

Serial depletion by species

The replacement of one species or subspecies by another, which results in the appearance of stable landings, has occurred in many nearshore marine fisheries, suggesting that the management of species complexes can be problematic (Dugan and Davis 1993; Orensanz et al. 1998). Alaskan crustacean fisheries were serially depleted as a succession of species suffered dramatic declines in their landings (Orensanz et al. 1998). Similarly, the serial replacement of subspecies has been suggested as a contributor to the collapse of the eastern Atlantic cod fishery (Hutchings and Myers 1994). Replacement of one subspecies of cod by another acted to maintain the illusion of a long period of stability in the cod fishery until a rapid, unforeseen, total collapse occurred when all the subspecies had been fished out.

In the California abalone fishery south of San Francisco, apparent stability from 1952 to 1968 was an illusion produced by landings comprised of multiple species and multiple fishing areas. When the fishery complex was divided into components, a pattern of serial decline by species and area emerged. Combined landings were bolstered by increases in red abalone landings, which maintained stability in the combined landings during the decline in pink abalone landings

Fig. 6. Green abalone catch (metric tons, bars) and number per hour (open squares) from southern California mainland and two Channel Islands. Catch is divided by landing periods. Catch areas are ordered from top to bottom by accessibility to fishery. Vertical lines around points are SE.



(Fig. 2). In 1971, there was an abrupt decline in pink abalone landings caused by increases in pink abalone size limits imposed by managers in an effort to protect stocks (Figs. 2 and 3). The spike in green abalone landings (1971) reflected a lowering of the green abalone size limit to placate fishermen after the pink abalone size limit increase. Red abalone also began to decline in this period, marking the start of intensive commercial fishing of green, black, and white abalone. Landings for these three species rapidly peaked and then declined. In the early 1970s, black abalone bolstered the combined landings.

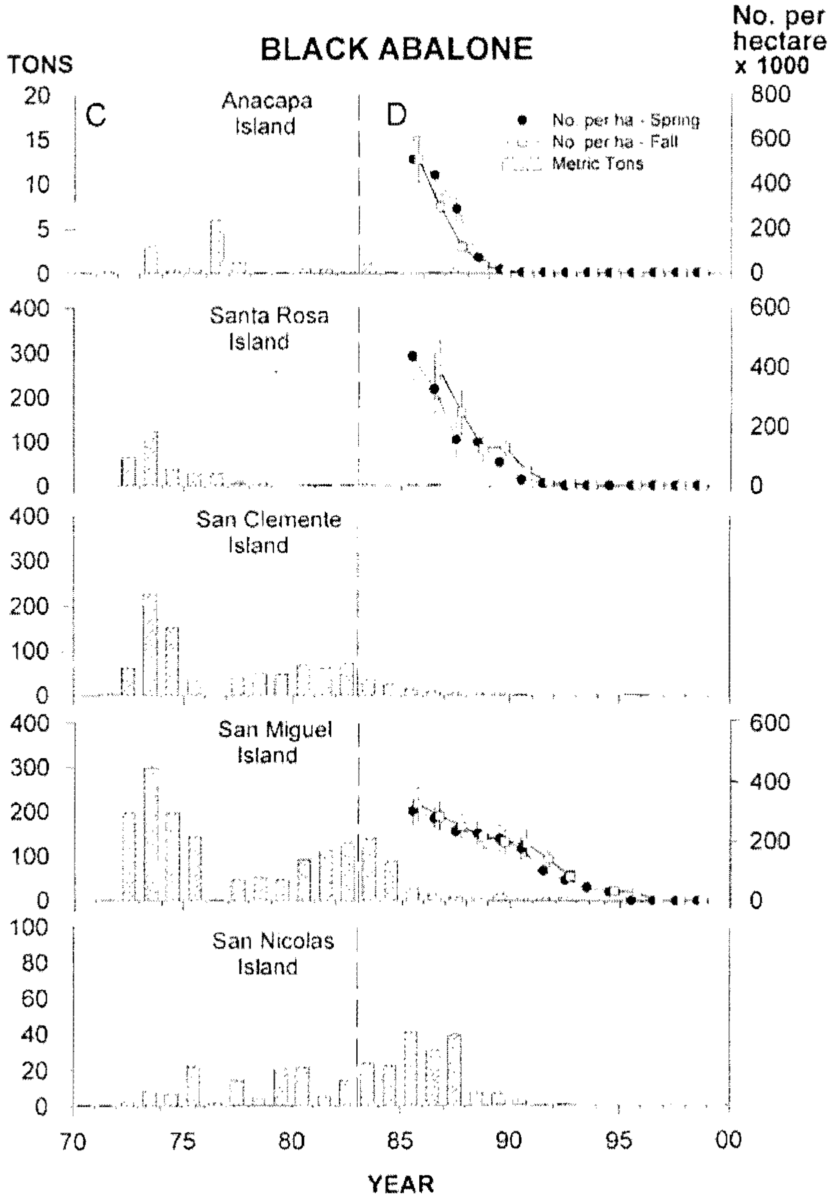
During the last period of the commercial abalone fishery, many commercial divers held both abalone and sea urchin permits. As the availability of abalone decreased, efforts were shifted to the growing sea urchin fishery. Since the abalone fishery was not closed, divers searching for sea urchin continued to land abalone even with populations at extremely reduced levels. Declines in commercial abalone landings were replaced by sea urchin landings, thus maintaining the value of the combined dive fishery at $10 million from 1955 to 1985, while abalone suffered dramatic declines (Dugan and Davis 1993).

Serial depletion by area

Spatially structured populations are particularly vulnerable to depletion by area. Orensanz et al. (1998) detailed the collapse of the Alaskan crustacean fisheries due to the serial depletion of fishing areas, with areas close to port being depleted first. In the California commercial abalone fishery, an analysis of the catch by area revealed a similar pattern of spatial serial depletion. Combined landings from the different catch areas (Figs. 4–8) masked the succession of declines in fishing areas. Landings appeared stable as abalone were fished from more distant locations while nearby fishing grounds were sequentially depleted. During the apparently sustainable period B, red abalone catches in most areas peaked midperiod and then began to decline (Fig. 4). The declines in red abalone catch were masked by combined landing increases through 1967 at the end of period B (Fig. 2, slope (m) = 40 $t \cdot year^{-1}$). Likewise, apparent stability in red abalone landings during period D (Fig. 2) reflected a shift to distant fishing grounds on San Miguel Island and in northern California (Fig. 4). In the commercial fishery, distant areas (typically islands) were the last strongholds for landings with red and black abalone at San Miguel and San Nicolas islands and pink abalone at Santa Cruz and San Clemente islands (Figs. 4, 5, and 7). Another factor apparently affecting the speed of the decline of abalone was the size of the area being fished. Relatively small islands, such as Anacapa and Santa Barbara islands, and Cortez and Tanner banks, were among the first to be depleted of abalone (Figs. 5, 7, and 8).

Remnant island populations of pink abalone, as indicated by fishery independent surveys in the early 1980s, could have been protected by a pink abalone closure or by area closures, but neither of these management strategies were implemented. Pink abalone populations may have been reduced to insufficient levels to generate successful recruitment. No evidence for pink abalone recruitment was found in our fishery independent surveys. These populations eventually collapsed in the mid-1990s (Fig. 5). Periods C and D (1969–1996) would have been the time to implement pink broodstock enhancement measures (Tegner 1992; Tegner 2000). This was clearly a missed opportunity for pink abalone restoration.

Fig. 7. Black abalone catch (metric tons, bars) and density (number per hectare, solid dots) from five Channel Islands. Catch is divided by landing periods. Catch areas are ordered from top to bottom by accessibility to fishery. Vertical lines around points are SE.

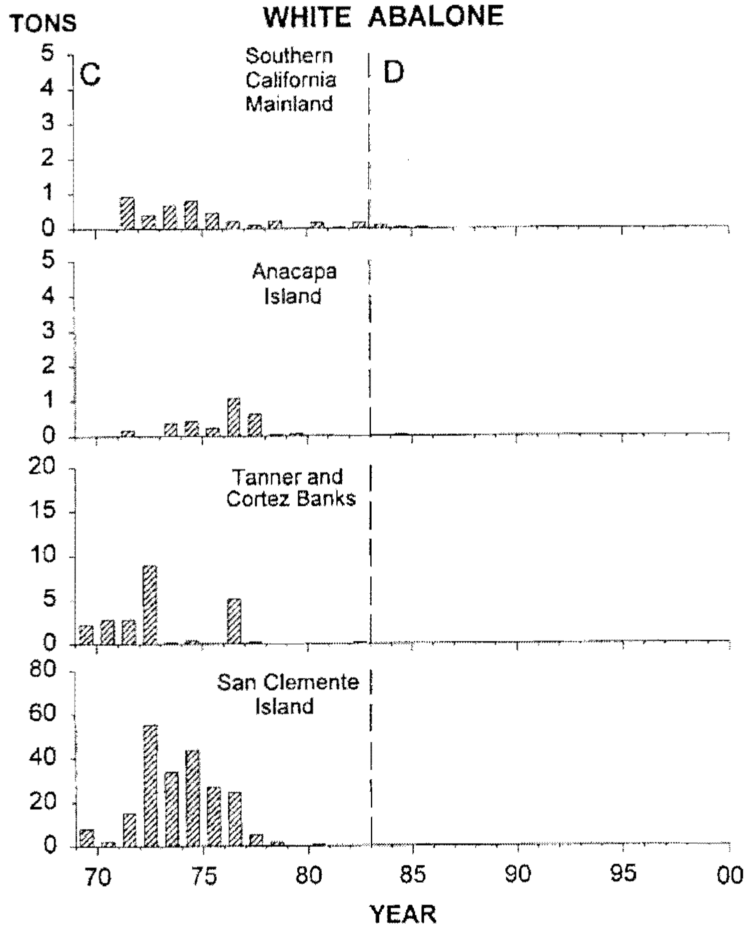


Commercial landings of red abalone in northern California and at San Miguel Island persisted in the 1990s (Figs. 4–8). Karpov et al. (1998) showed that red abalone at San Miguel Island were the last to be impacted by the commercial fishery, being furthest from the mainland. San Miguel Island is also in a more suitable water circulation pattern for this cold water species (Engle 1994; Tegner et al. 1992). However, the sustained commercial catch of red abalone in northern California south of San Francisco (Fig. 1) during period D is puzzling. Fishery independent surveys in 1993 on the fishing grounds in this area at Half Moon Bay revealed low densities averaging only 200 abalone · ha^{-1} (K. Karpov, unpublished data). One possible explanation for this disparity between fishery-dependent and -independent data is poaching from recreation-only areas north of San Francisco, which were then reported as landings from the open northern California commercial area (Daniels and Floren 1998).

Magnitude of decline

Landings in California have declined precipitously. Fisheries-independent data collected during periods C and D revealed that levels of decline observed in fishery landings presaged stock collapse. Declines in red abalone populations today are a major concern for fishery managers because this is now the only abalone in California abundant enough to support a fishery. Persistence of red abalone, as compared to some of the other species in the commercial landings, may be a reflection of differences in distribution and vulnerability to exploitation. Commercial landings of red abalone in central and southern California averaged 461 t · $year^{-1}$ from 1950 to

Fig. 8. White abalone landings (metric tons, bars) from southern California mainland, two Channel Islands, and two offshore banks. Catch is divided by landing periods. Catch areas are ordered from top to bottom by accessibility to fishery.



1996. Recreational catch north of San Francisco averaged 920 t · year^{-1} from 1985 to 1989 (Tegner et al. 1992). The red abalone has the broadest depth range of the abalone species in California (Tegner et al. 1992; Tutschulte 1976).

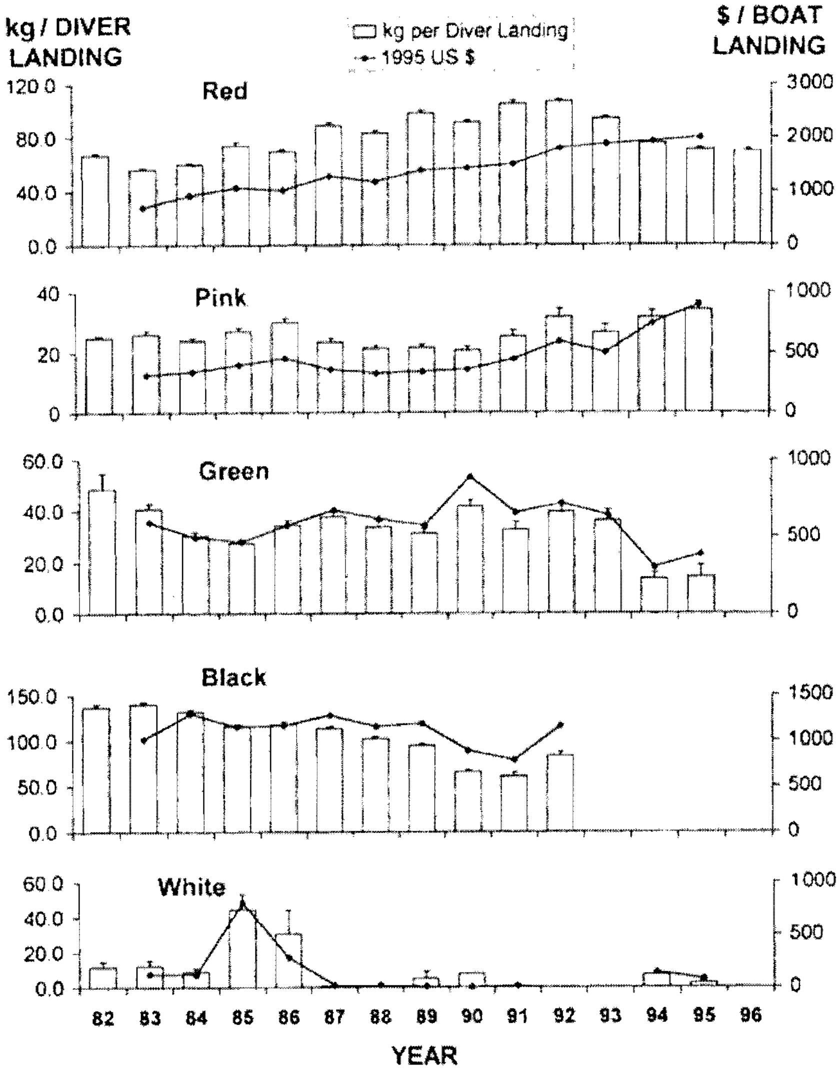
Pink abalone were the second most persistent species in catch. Pinks were the most widely distributed of the four southern species. Cox (1962) attributed a portion of the decline in pink abalone during period B to the combined effects of slow growth and starvation due to reductions in kelp biomass during the 1957–1959 El Niño.

The fisheries for the green, black, and white abalone, all with narrower depth and geographic distributions, were short-lived. Green abalone are a shallow subtidal species abundant in surf grass beds. This species was fished hard during period C and thereafter contributed little to the commercial fishery. Black abalone have a wide geographical distribution, but a narrow depth distribution restricted to the lower- and mid-intertidal zone. An added concern for black abalone is the combined effects of fishing and withering foot syndrome (Alstatt et al. 1996; Haaker et al. 1992). While landing declines occurred prior to the outbreak of this lethal disease, continued take further contributed to the potential extirpation of this species by removing remaining individuals that may have been resistant to the disease. White abalone have a narrow, deep distribution from 25 to 50 m on rocky habitat. Davis et al. (1998) reported extreme declines in white abalone abundance following commercial and sport exploitation. During extensive surveys in the 1990s at the Channel Islands, using deep diving and a manned submarine, divers found <2 white abalone · ha^{-1}, compared to 2000–10 000 · ha^{-1} in the 1970s at comparable depths (Tutschulte 1976). Davis et al. (1998) suggest that unless active restoration methods are enacted soon this species may become extinct. The white and black abalone are currently candidates for federal endangered species status.

Factors contributing to management failure

A number of factors undermined effective management action in addition to ignoring the possibility of serial depletion by species and by area. Management effort was limited to conventional strategy that primarily focused on size limits to protect stocks (Tegner et al. 1992). This perspective was based on egg-per-recruit models that assume several years of spawning success for a significant portion of the abalone population prior to reaching the minimum size for take (Tegner et al. 1989), derived from the potentially high fecundity of abalone (Giorgi and DeMartini 1977). We show that this management approach did little to ensure the sustainability of abalone resources. Focus on spawning potential ignores effects of protracted periods of recruitment failure under intense fishing

Fig. 9. CPUE (kilogram per diver landing, bars with SE) for red, pink, green, black, and white abalone and values per boat landing (solid line).



pressure (Sluczanowski 1984). Another factor may have been the loss of adult aggregations needed for spawning success (Shepherd and Brown 1993). Low densities can result in fertilization failure in free-spawning invertebrates (Pennington 1985; Levitan et al. 1992). Recruitment of young abalone may not be successful every year (Karpov et al. 1998; Rogers-Bennett and Pearse 1998). Karpov et al. (1998) reported only one red abalone recruitment event in 4 years in northern California where deep water (>8.5 m) stocks were protected. Likewise, Tegner et al. (1989) found a single recruitment peak of red abalone in a study area on Santa Rosa Island over a 5-year period.

Ultimately, during the final period of abalone decline, reliance on CPUE data further delayed closures. CPUE for abalone is a poor index of abundance, as has been shown for other spatially structured fisheries (Orensanz et al. 1998). Assumptions for use of CPUE, including the redistribution of the stock and random fishing (Gulland 1983; Ricker 1975), are violated in the abalone fishery as they are in other fisheries for sessile benthic invertebrates. CPUE for red and pink abalone (1983–1996) increased throughout much of period D, during the time when red abalone landings remained consistent and pink abalone declined (Figs. 2 and 9). Two factors during this time worked to increase CPUE: (*i*) improvements in locating sites using Loran and Global Positioning Systems (GPS), and (*ii*) increased search time of fishing grounds by abalone and urchin divers in the dual fishery.

Although the economic value of this resource was high, little funding was directed at research or assessment during the successful period of the fishery and at conservation when several species were clearly in decline. Commercial landing taxes were limited to US$0.03 · kg^{-1} until the 1990s when an added enhancement and restoration tax of $0.43 · kg^{-1} was established. Enhancement funds were used primarily for stocking hatchery-reared juveniles and not stock assessment. Restocking programs moved forward with abalone juvenile seed supplied by the abalone aquaculture industry, but there was little follow-up work quantifying success rates. The few studies that were conducted examining abalone juvenile restocking success suggested that survival was <1% (Tegner and Butler 1989; Rogers-Bennett and Pearse 1998). Restocking programs functioned to dissipate the resolve and funding needed for more conservative management strategies (Tegner 2000), a situation that has been repeated in other fisheries (MacCall 1989).

Increasing abalone value was another factor that further delayed conservative management action during the decline. As the landings declined the value increased exponentially, in response to demands from foreign markets and a growing population in California (Fig. 2). Increases in value intensified political pressures to continue fishing despite evidence of collapsing stocks. In this case market forces did not work to stop the fishery as the species declined and the economics of the dual fishery permitted the fishing of abalone species to near extinction.

A final factor, not considered in this paper, was the added impact of a growing SCUBA-based sport fishery in southern California (Karpov and Tegner 1992; Tegner et al. 1992). Beginning in the 1970s, this largely unmonitored fishery had a growing impact on abalone stocks on the mainland and Channel Islands. We focused on commercial landing statistics as the best fisheries-dependent record of the magnitude of decline resulting from various cumulative impacts. This paper was not intended to identify the degree of relative impacts from fishery, pollution, or the various nonanthropogenic factors.

Conclusions

In this study, we outline the case history of the failed abalone fishery in California south of San Francisco, which ended in the 1997 closure. Management strategies, including minimum size limits, season closures, and limited entry did little to prevent declines of individual species in the abalone complex or declines in catch areas. CPUE data did not forecast fishery declines and increased abalone values exacerbated fishing effort. Failure to examine landing data by species and catch by fishing grounds delayed management actions restricting fishing. Management lacked the flexibility to respond to dramatic declines in catch areas to allow for spatial closures such as closing Anacapa Island, which declined early in the fishery. In fact, the burden to prove that there were problems with the landings rested on managers rather than on fishers (Dayton 1998). Areas were not closed when they showed clear signs of decline because landings remained high elsewhere as fishers concentrated their efforts in new areas of high resource abundance. Our analyses show this was serial depletion by area. Many of the depleted areas did not recover, i.e., the mainland in southern California, despite long closures (25 years) enacted well after landings had declined. Our findings also support Dugan and Davis (1993) that component species were serially depleted. Today, several species have been reduced to such low levels that recovery without human intervention may be impossible and may be a challenge even with costly enhancement measures. The added impacts of nonfishery-related pressures such as El Niño, disease, and predation by sea otters may now drive populations to extinction.

The use of the precautionary principle in fishery management might have prevented this type of fishery disaster. This principle requires that, in the absence of information, fishery management should be conservative (Food and Agriculture Organization of the United Nations (FAO) 1996). In the case of the California abalone, localized catch declines in the absence of fishery independent information would have required earlier closures. Edwards (1913) was the first to recognize that local declines in abalone could ultimately lead to loss of the resource as a whole. He was visionary in suggesting the establishment of protected reservations to function as breeding centers for abalone at 5–10 mile intervals along the coast. This plan to establish marine protected areas (MPAs) for abalone could only be used in areas that still support minimum viable populations. Today, red abalone populations on the north coast of California are protected by a large-scale refuge by depth since fishing is restricted to breath-hold divers and landings in this fishery appear to be stable (Karpov et al. 1998). In southern California, new and creative solutions are needed to restore abalone stocks. If stocks do recover and fishing is reestablished, new and more conservative management approaches in addition to MPAs will be needed to prevent future collapse. An example might be to allow breath-hold only diving for pink abalone and other species once refuge populations in deeper water are reestablished.

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