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The rise of invertebrate fisheries and the fishing down of marine food webs in California

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Invertebrate fisheries are growing in importance worldwide and are now California's most important fisheries by both volume and value. There has been a 174% increase in the value of marine invertebrate fisheries in California since 1980. Although there is a long tradition of fishing for invertebrates in California, recently there has been a rise in their importance and they now (2008–2012) comprise four of the top five fisheries by value. In the 1980s, finfish fisheries dominated both the value and the volume of landings. Finfish and invertebrates were comparable in the 1990s in terms of both value and landings. Since 2000, there has been a shift toward invertebrate fisheries due to decreases in finfish fisheries, increases in invertebrate fisheries, and increases in novel or emerging invertebrate fisheries. The trends observed in California fisheries are consistent with the hypothesis that marine food webs have been fished down. In the 1980s (1980–1989), 90% of the top fisheries by value were for predators, while in the recent past almost half of the top fisheries species were from lower trophic levels such as herbivores and scavengers. This trend in the expansion of California invertebrate fisheries follows global fishery trends. In the eastern Pacific Ocean, there has been a 400% increase in the landings of invertebrate fisheries from 1950 to 2011. Despite this growth, fishery assessment and management of invertebrate fisheries are lagging behind. As we work to sustainably manage California invertebrate fisheries it is imperative that we continue to advance our knowledge of their biology, life history, and drivers of population fluctuations in a variable ocean environment.

Key words: California fisheries, catch, emerging fisheries, fishing down, fishery management, invertebrates

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Invertebrates now dominate California fisheries in terms of both landings and value. Traditionally, the image of California fisheries has been characterized by finfish, including salmon (*Oncorhynchus* spp.), rockfish (*Sebastes* spp.), tuna (*Thunnus* spp.), sardines (*Sardinops sagax*), and sablefish (*Anoplopoma fimbria*). Yet today, four of the top five grossing fisheries are invertebrates with sablefish as the only finfish in the top five. Invertebrates have been on the rise in terms of landings by weight and value since the 1980s. Recognition of the importance of invertebrate fisheries, also known as shellfish fisheries (crustaceans, mollusks, and echinoderms), has developed slowly (but, see Rogers-Bennett 2002, Mason 2004). California squid and crab fisheries were worth a total of $152 million ex-vessel in 2012 compared with the total for groundfish and salmon of $32 million. With these changes in the landscape of California fisheries the question arises as to whether management funding and priorities will adapt once invertebrate fisheries are recognized as the most important fisheries in the state.

This rising trend of invertebrate fisheries in California has also been observed around the world. Food and Agriculture Organization statistics (FAO) show that from 1984 to 1995 there was a 46% increase in the catch of invertebrates (Perry et al. 1999). In the Pacific Northwest, the change was greater with Canadian invertebrate fisheries increasing 130% over the same period (Perry et al. 1999). Globally, this trend is part of a bigger picture of fishing out long-lived species (Jennings et al. 1998) and fishing down predators in marine food webs (Pauly et al. 1998). There may also be shifts in marine communities that favor invertebrates, such as the presence of large scale jellyfish blooms, taking place as a result of fewer predatory finfish (Mills 2001). The growing importance of invertebrate fisheries necessitates increased research including quantifying spatial and temporal patterns in landings, determining life history parameters, examining key drivers of productivity, and developing strategies for sustainable invertebrate management.

Invertebrate populations are, however, notoriously difficult to manage. Invertebrates tend to have poor stock per recruit relationships and poor yield per recruit relationships (Caddy 1989). On top of this, we know that even for well-studied finfish, fishery management has not always been successful (Walters and MacGuire 1996, Pauly et al. 2002). Despite their productivity, invertebrate populations are not immune to overfishing and fishery collapse. The white abalone (*Haliotis sorenseni*), once part of the commercial abalone fishery in California, is now found at exceedingly low densities (<1% of the estimated baseline) and is on the verge of extinction (Hobday et al. 2001, Rogers-Bennett et al. 2002). In 2001, white abalone was added to the federal endangered species list (US Federal Register 2001), and at least one other marine snail has gone extinct in the last century (Carlton et al. 1991). Exploited marine invertebrates are particularly vulnerable to local extirpations based on local population genetics (Thorpe et al. 2000), fine scale distribution (Orensanz and Jamieson 1998), and high market value (Purcell et al. 2014).

Fisheries management principles have been based on concepts derived largely from finfish (Caddy 1989), such as the work of Beverton and Holt (1957) using North Sea groundfish that are long-lived and relatively easy to age. Similarly, the concept of stock recruitment relationships came from smolt production in salmon (Ricker 1976). Surplus production models were first developed for use with Pacific tuna biomass due to problems associated with aging tunas (Gulland 1983). Yet, managing invertebrates may not simply be a matter of applying strategies developed for finfish (Perry et al. 1999) but rather developing whole new approaches to sustainably manage invertebrate fisheries (Winemiller 2005). One way forward for benthic invertebrate management was suggested by Thorson (1957), who argued the importance of examining and maintaining sustainable densities.

In this paper, we examine trends in the landings and values of California marine fisheries from 1980 to 2012, dividing fisheries into invertebrates and finfish. We look for patterns in the relative dominance of invertebrate fisheries over space and time. We examine patterns in the fisheries across regions in California from the north, central, and southern coasts as well as nearshore, benthic, and pelagic habitats. We examine the fishery landings data to see if they are consistent with the hypothesis that there are fewer predators in the top ten fisheries today. Finally, trends in invertebrate landings are also examined across the wider spatial scale of the eastern Pacific Ocean.

Methods

We examined landings data of marine commercial fisheries in California from the Marine Fisheries Statistical Unit of the California Department of Fish and Wildlife (CDFW) from 1980 to 2012. This time period encompasses three distinct decadal time periods: 1980–1990, 1991–2000, and 2001–2012, which allowed us to examine the hypothesis that there has been a shift from finfish to invertebrates comprising California's most valuable fisheries. Landings summary data were extracted from the CDFW California Fisheries Information System (CFIS) database where daily landing receipt records are maintained. Landings summary information included year of landing, port where landed, total pounds caught, and ex-vessel value for each species or species complex. Species landings were categorized by year as either invertebrates or finfish. Pounds landed were converted to metric tons (t). Value data from 1980 to 2011 were adjusted for inflation to 2012 dollars using the Consumer Price Index (Bureau of Labor Statistics 2014).

Annual landings were summarized by one of three regions based on port of landing: northern (Mendocino County to the California-Oregon border), central (Sonoma County to Point Conception), and southern (south of Point Conception to California-Mexico border). Landings were classified by habitat by categorizing each species according to its life history traits as demersal, sessile, or pelagic. Demersal and sessile species were then further defined by general fishing depth, either nearshore (≤50 m depth) or offshore benthic (>50 m).

The species with the highest average ex-vessel price per kilogram was examined for the period from 2008 to 2012. Average price was calculated by dividing the sum total value by the sum total landings from 2008 to 2012. Only those species that had substantial landings, which we defined as more than 2.3 t, during the time span were considered.

Changes in the trophic level of the top 10 fisheries over time were examined by comparing trophic levels dominating the catch from the first and last decades of the time series. Each of the top 10 species was characterized by one of three trophic levels: predator, herbivore, or scavenger. The ranking was determined by the sum total value of each fishery during the decade. Percentage of each category was calculated using the total value for each trophic level divided by the total value of the 10 species during this time period.

The values (adjusted for inflation) from 1980 to 2012 of the four most valuable invertebrate fisheries and two emergent fisheries were examined. The top four invertebrate fisheries were market squid (*Doryteuthis* [*Loligo*] *opalescens*), Dungeness crab (*Metacarcinus* [*Cancer*] *magister*), spiny lobster (*Panulirus interruptus*), and red sea urchin (*Mesocentrotus* [*Strongylocentrotus*] *franciscanus*), and two then emergent invertebrate fisheries for sea cucumber, which includes warty sea cucumber (*Parastichopus parvimensis*) and giant red sea cucumber (*P. californicus*), and Kellet's whelk (*Kelletia kelletii*).

Eastern Pacific Ocean landings data from 1950 to 2011 (FAO 2014) were reported as capture production in metric tons and include subsistence, commercial, and recreational catch for marine invertebrate species. This dataset for the eastern Pacific Ocean includes two regions, the Central Pacific and North Eastern Pacific (Latitude: 60° N to 25° S, Longitude: 175° W to 77° W), which encompass the West Coast of the United States.

Results

There is a clear increasing linear trend in the value of invertebrate fisheries in California as a percentage of the total fisheries value over time (Figure 1). From 1980 to 2012, the total value of invertebrate fisheries grew by 174% (Figure 2a). Conversely, the value of finfish declined sharply by 96% (Figure 2a). A 90% decline was also observed in the catch of finfish during the same time period (Figure 2b). There was a steep and steady rise (increase of 223%) in landings of invertebrate fisheries in California from 1980 to 2012 (Figure 2b). At the same time, there was a sharp drop of 81% and 61%,

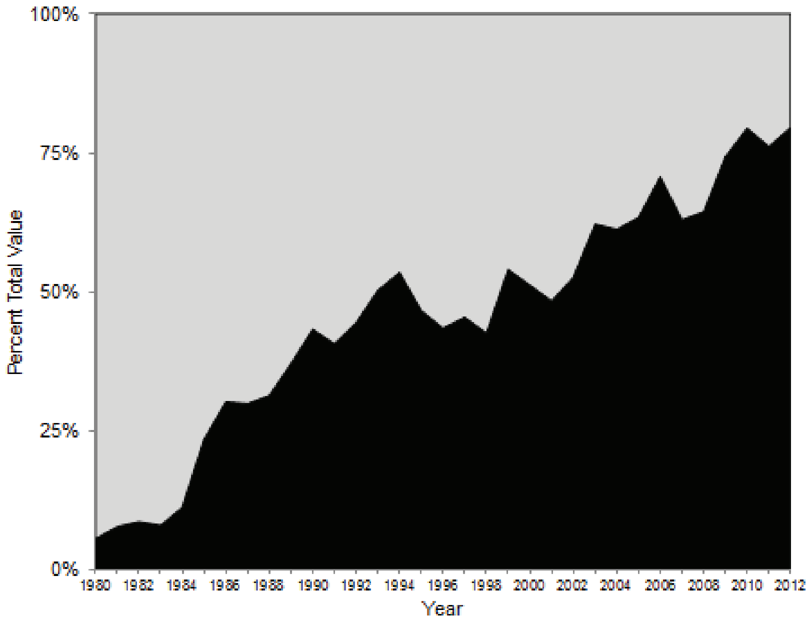
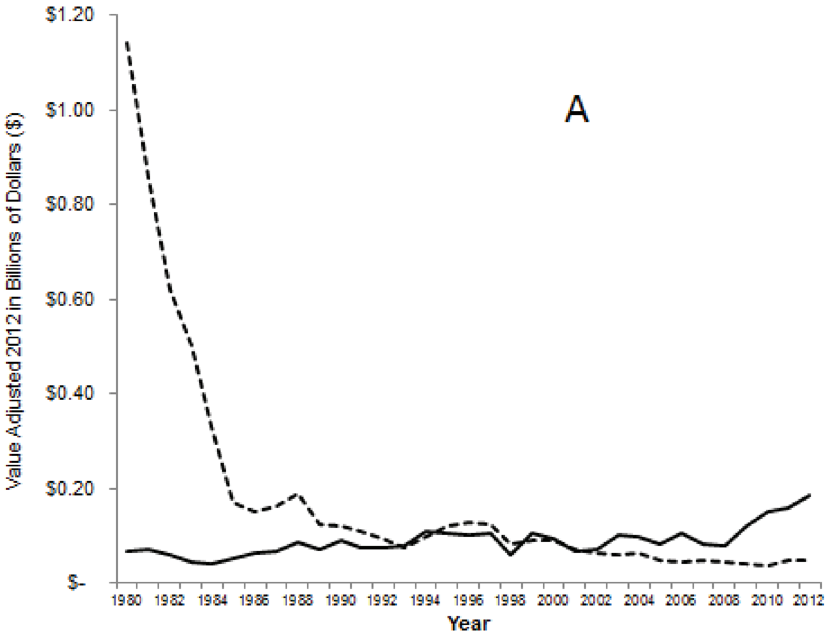


Figure 1.—Percent of the total value of invertebrate (black area) and finfish (gray area) commercial marine fisheries in California, USA from 1980 to 2012.

respectively, in the total value and landings of California fisheries from 1980 to 2012 (Figure 2a, Figure 2b). From 1980 to 1990 finfish made up the majority of the total value. From 1991 to 2000, approximately half of California fisheries value came from invertebrates as their value increased over this time period. In the most recent time period, 2001–2012, more than 50% of the total value of all California fisheries was derived from invertebrate fisheries (Figure 1).



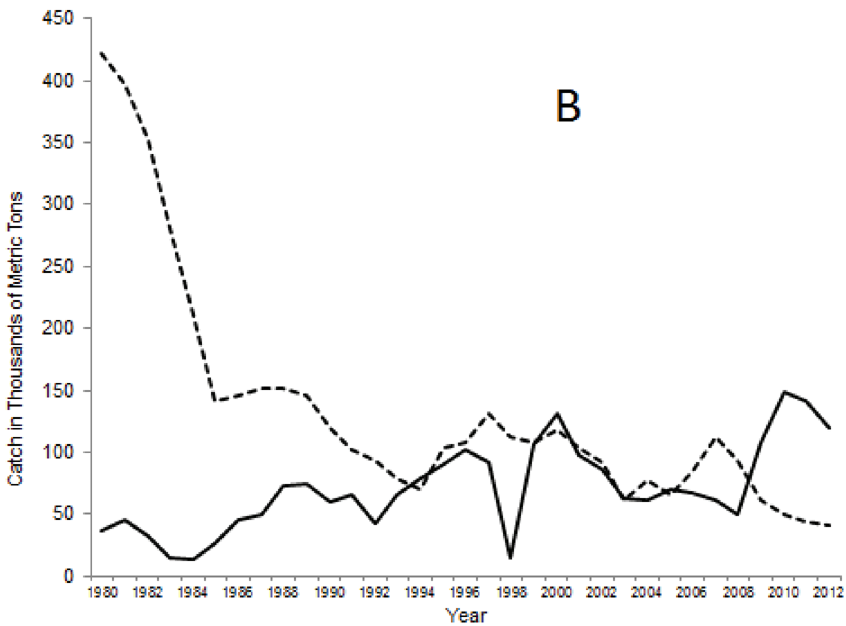


Figure 2.—Total value (a) of California's commercial fisheries in billions of dollars, and total catch (b) in thousands of metric tons from 1980 to 2012 for invertebrates (solid line) and finfish (dashed line). Yearly value is adjusted for inflation to year 2012 dollars with the Consumer Price Index (Bureau of Labor Statistics 2014).

Invertebrates made up four out of the top five fisheries in California from 2008 to 2012 (Table 1). Market squid, Dungeness crab, and spiny lobster were the top three fisheries by value, while sablefish and red sea urchin rounded out the top five (Table 1). The high-value fisheries in terms of annual average price per kilogram, from 2008 to 2012, were dominated by invertebrate fisheries in the top three positions (Table 2). Spiny lobster was the top fishery by price, followed by spot prawn (*Pandalus platyceros*) and sea hare (*Aplysia californica*). The five next most valuable species were rockfish, many of which are sold live in the local restaurant trade. The mantis shrimp (*Hemisquilla californiensis*), object of a relatively small fishery, was next highest and followed by kelp greenling (*Hexagrammos decagrammus*), another live market finfish.

TABLE 1.—Average annual value of the top five commercial marine fisheries, California, USA, 2008–2012.

Ranking	Common Name	Millions of U.S. Dollars per Year
1	market squid	58.0
2	Dungeness crab	46.3
3	California spiny lobster	10.8
4	sablefish	10.3
5	red sea urchin	7.7

TABLE 2.—Average price per kilogram of the top ten commercial marine fisheries, California, USA, 2008–2012.

Ranking	Common Name	Price ($US) per kg
1	California spiny lobster	31.32
2	Spot prawn	24.49
3	Sea hare	21.37
4	Grass rockfish	20.52
5	Treefish	19.14
6	China rockfish	16.34
7	Black-and-yellow rockfish	15.53
8	Gopher rockfish	15.35
9	Mantis shrimp	14.64
10	Kelp greenling	13.74

When we examined the value of landings trend by region within the state, invertebrate fisheries in the southern California region exhibited the greatest increase, from 4% of the catch value in 1980 to 34% by 2012, with a high of 50% in 2009 (Figure 3). However, in the southern region, the value of finfish declined markedly from 80% in 1980 to 40% in 1990, and to just 6% of the total value in 2012. In central California, invertebrate fisheries did not rise above 15% until 2002, up dramatically from 2% in 1980, but then declined in 2009 to about 6%, while in the last three years of the period they made up about 20% of total value. Coincidentally, finfish in the central region increased from 7% in 1980 to a high in 1991 of 31%, and then fell to about 10% in 2012. Northern California invertebrates made up <10% of the total value in the 1980s, began to increase in the 1990s to between 11% and 20%, and continued this trend in the 2000s from a low of 8% to a high of 26% in 2012. Finfish in the northern region changed little from 1980 to 2012, remaining at 5% of total landings. However, they did experience an increase from 1985 to 1997 of between 11% and 15% of total value.

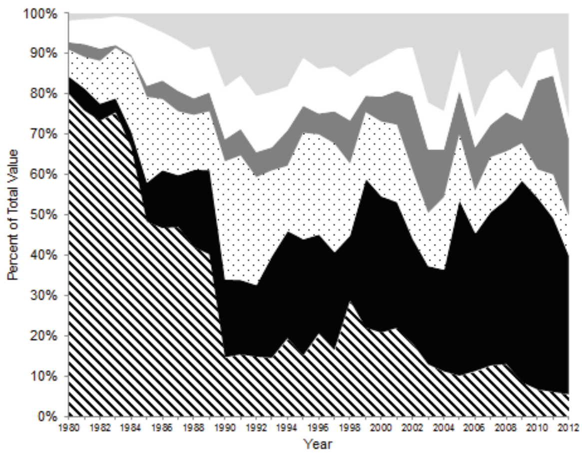


Figure 3.—The geographic distribution of the value, as percent of total value, of invertebrate and finfish commercial fisheries in northern, central and southern California from 1980 to 2012. The regions and fisheries are represented as follows (from top of graphic): northern invertebrates (light gray), northern finfish (white), central invertebrates (dark gray), central finfish (dotted pattern), southern invertebrates (black), and southern finfish (diagonal stripes).

Invertebrates in both the benthic and pelagic habitats exhibited the most dramatic increases in percent total value from 1980 to 2012 (Figure 4). Benthic invertebrates comprised 3% of total value in 1980, rose past 30% by 2003, and climbed to a high in 2012

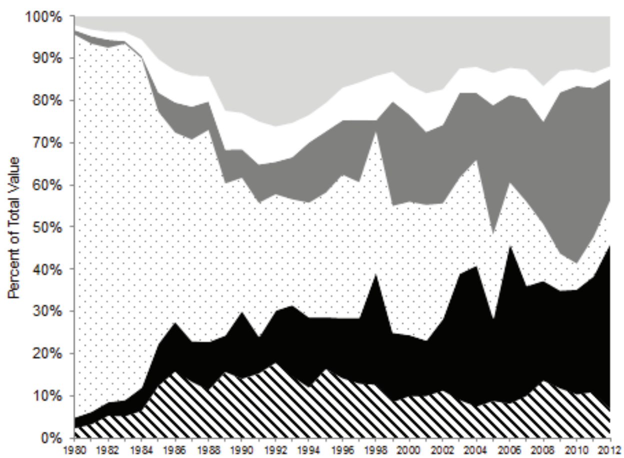


Figure 4.—The habitat distribution of the value (percent of total value) of invertebrate and finfish commercial fisheries in nearshore, pelagic and benthic habitats in California from 1980 to 2012. The habitats are defined as nearshore (≤50 m depth), pelagic (in the water column), and benthic (>50m depth). The habitats and fisheries are represented as follows (from top of graphic): nearshore invertebrates (light gray), nearshore finfish (white), pelagic invertebrates (dark gray), pelagic finfish (dotted pattern), benthic invertebrates (black), and benthic finfish (diagonal stripes).

of 41%. The pelagic invertebrates rose from a low of 1% in 1980, surpassing 20% in 1999, to a high of 41% in 2010 and were at 28% in 2012. Nearshore invertebrates rose from 2% in 1980 to a high in 1992 of 27%, then fell to <16% after 2003. Contributing to these increased invertebrate percentages was the precipitous decline in pelagic finfish from 88% in 1980 to 32% in 1989, and finally dropping below 10% by 2009. Nearshore and benthic finfish, however, changed very little between 1980 and 2012, and never exceeded 20% of value during the entire time series (Figure 4).

The last decade saw some of the peak fishery years for the top three ranked invertebrates (Figure 5a, Figure 5b). Market squid was the most valued species on average for the last five years (Table 1), and reached a peak ex-vessel value in 2010 of $78 million.

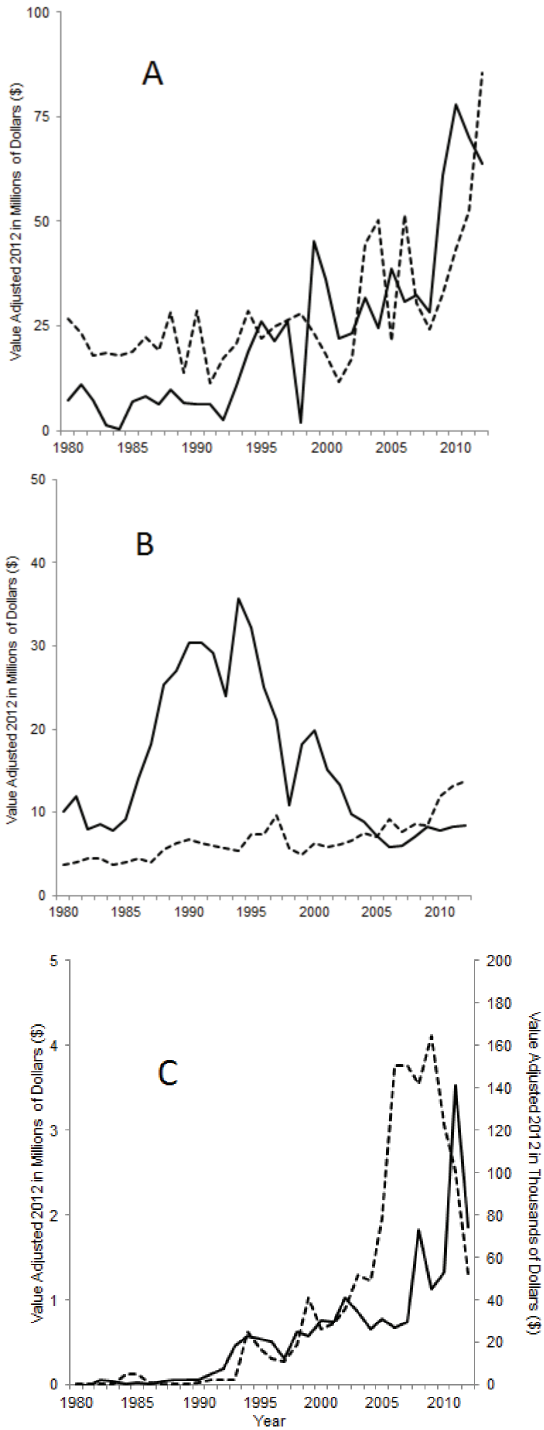


FIGURE 5.—Total value (in millions of dollars) of individual species of some of the top invertebrates in California commercial fisheries from 1980 to 2012: (a) market squid (solid line) and Dungeness crab (dashed line); (b) red sea urchin (solid line) and spiny lobster (dashed line); and (c) sea cucumber (solid line), in millions of dollars (left vertical axis), and Kellet's whelk (dashed line), in thousands of dollars (right vertical axis). Yearly value is adjusted for inflation to 2012 dollars using the Consumer Price Index (Bureau of Labor Statistics 2014).

Market squid has rapidly increased in value and, by 2012, it was 8.5× the value in 1980 (Figure 5a). The Dungeness crab fishery is generally characterized by cyclical landings, but trended upward since 1980, and rose in value since 2001 (Figure 5a). On average, crab was the second most valuable fishery in the state after market squid (Table 1); in 2012, the fishery reached a maximum of $85.6 million in total value, a historic high.

Spiny lobster was another high-value fishery as measured by total value and price per kilogram (Tables 1 and 2). The fishery steadily climbed since 1980, when it brought in $3.7 million. It increased to $13.8 million during the most recent year (2012), which was a record for that fishery (Figure 5b). A major invertebrate fishery that did not increase steadily in value since 1980 was red sea urchin (Figure 5b). The value of the red sea urchin fishery has undergone a classic boom and bust cycle, with the boom from 1989 to 1996, and peaked in 1994 at $35.7 million. Despite the nearly five-fold decline from this maximum to its average value during 2008–2012, it remained one of California's five most valuable fisheries (Table 1), and the value of the southern California landings continues to make this an important fishery in the state.

Both the sea cucumber and Kellet's whelk fisheries were low-value in the 1980s, but value of both fisheries increased during the 1990s by an order of magnitude and continued to rise rapidly thereafter (Figure 5c). This increase began in 1991 for sea cucumber ($126,400) and in 1994 for Kellet's whelk ($25,200). For the recent five-year period, the sea cucumber fishery was the 13th most valuable in California, and reached >$3.5 million in 2011, a record for the fishery. The smaller Kellet's whelk fishery, meanwhile, reached a peak year in 2009 of more than $164,600, more than 6.5× its 1994 value.

Along with the rise in invertebrate fisheries we saw an increase in the number of lower trophic level species making up the top ten fisheries in California (Figure 6). The

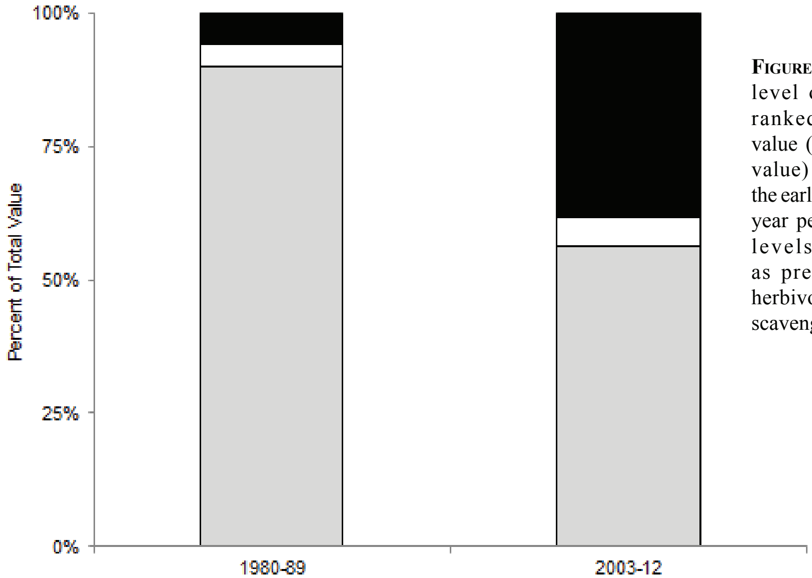


Figure 6.—The trophic level of the top ten ranked fisheries by value (percent of total value) calculated for the early and recent ten-year periods. Trophic levels are defined as predators (gray), herbivores (white), or scavengers (black).

species that made up the top 10 fisheries in the state were predominantly predators (90%) in the 1980s, while in the most recent decade they were divided about equally between predators and lower trophic level species (herbivores and scavengers; Figure 6). When yellowfin tuna (*Thunnus albacares*), a tropical species found offshore, were removed from the trophic level analysis, predators represented 75% of the top ten fished species in the 1980s, but the recent ten-year period remained unchanged.

The increasing trend in the tonnage, and hence value, of invertebrate fisheries also occurred across the eastern Pacific Ocean (Figure 7). In this region, invertebrate fisheries increased to 4× the value they were in 1950.

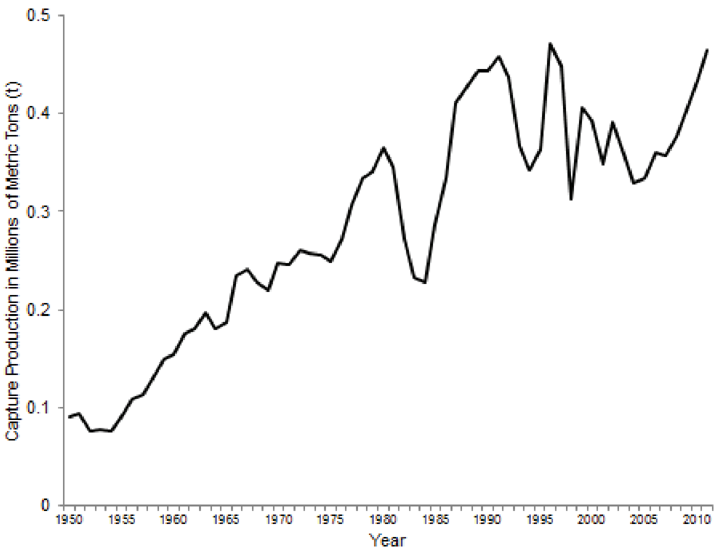


FIGURE 7.—Invertebrate fisheries capture production from the eastern Pacific Ocean in millions of metric tons from 1950 to 2011 as reported by the Food and Agriculture Organization of the United Nations (FAO 2014).

DISCUSSION

Fishery trends in California.—Invertebrates make up the majority of the value of California fisheries. Since 1980, there has been a steady, linear increase in the proportion of the total value made up by invertebrate fisheries, starting at <10% and increasing to >75% of the total fisheries value in 2012 (Figure 1). In addition, we have seen a rise in some of the traditional invertebrate fisheries such as spiny lobster and Dungeness crab, as well as the emergence of novel invertebrate fisheries after 1980. Two of the more recent invertebrate fisheries that have expanded since 1980 include those for market squid and red sea urchin (Figure 5a, Figure 5b), the first and fifth most valuable fisheries in the state (Table 1). The market squid fishery grew rapidly in fleet size and landings in the 1980s due to increasing world-wide demand. Market squid is a high volume fishery with landings that began to increase in the early 1990s, reaching 100,000 t for the first time in the 1996–1997 season. During 2008–2012, the average annual invertebrate fisheries catch was 113,094 t, with market squid accounting for 96,292 t (85%) of the total by weight. The peak in red sea urchin landings was fueled by an ever-increasing market demand, which precipitated the increase in landings from the northern California portion of the fishery, where previously unexploited stocks were quickly fished down and reduced by almost 90% (Kalvass and Hendrix 1997). Red sea urchin landings in southern California have fallen more slowly, declining by >50% since the peak in 1990. Since the 1980s, sea cucumber and Kellet's whelk have also contributed to the overall value of invertebrate fisheries (Figure 5c).

Dungeness crab and spiny lobster, two mainstays of California invertebrate fisheries over many decades, have also expanded since 1980 (Figure 5a, Figure 5b) and are now two of the top five most valuable fisheries in the state (Table 1). During the 2010–2011 Dungeness crab season, the majority of landings came from central California, a shift from northern California that had traditionally produced the majority of the landings. The recent record crab years have been driven by increased landings from central California, coupled with higher-than-average landings in the north and higher than average ex-vessel prices ($5.53/kg). Records of spiny lobster landings since 1917 peaked in the early 1950s. Since 1980, there has been a steady rise in lobster landings with some of the recent years near the historic peak, as well as a concomitant increase in value. This suggests that the productivity in this fishery has benefitted from warmer oceanographic conditions since 1980 (NOAA 2014). Regulation changes in 1976 requiring lobster traps with mandatory escape ports might also have bolstered fishery productivity during the last 30 years.

Coincident with the increase in invertebrate fisheries since 1980, the overall value of California fisheries has declined sharply (Figure 2a). This decline is particularly concerning since landings by weight have not been declining (Mason 2004). The value of finfish dropped from a high of >$200 million in 1979 to $46 million in 2001 (Mason 2004), and have not increased since then (Figure 2a). The steepest decline was during the 1980s, when a combination of factors, including the relocation of California's high-value tuna fisheries, impacted the value (Figure 2a). During the early 1980–1984 period, subtropical tunas (yellowfin tuna, Pacific bluefin tuna (*Thunnus orientalis*), and blackfin tuna (*Thunnus atlanticus*), made up 29% of the finfish landings value but, after that, they had little impact on the landings. The relocation of California's subtropical tuna fishery was due, in part, to socio-economic factors arising from the requirement for "dolphin-safe" canned tuna, which effectively removed the Eastern Tropical Pacific fishing grounds from availability to the U.S. fleet. The abundance of subtropical tunas in California waters prior to 1985 was also impacted by the warm water years, such as the strong El Niño in 1983–1984, when the tunas shifted their distribution north into California (Mason 2004, Norton and Mason 2004). Since 1985, subtropical tunas have made up less than 10% of the finfish landings. If we remove subtropical tunas from the analyses, there is a slight decrease in the total value (vertical axis in Figure 2a) but no change in the dramatic downward trend of the finfish fisheries compared with the rise of invertebrates in value and catch.

The decline in finfish in the 1980s can also be seen regionally in the sharp decline of finfish landings from northern and southern California, with finfish values holding relatively steady in central California until 2002 (Figure 3). The value in the central coast was maintained, in part, due to the emergence of the live fish market where rockfish and other nearshore fishes are caught and sold alive at a premium price. In the past decade however, the value of finfish landings has declined even in central California despite the high price per kilogram for many nearshore finfish (Table 2). Management measures such as gear restrictions, closed fishing areas, and quotas implemented during this time period have been responsible for declining rockfish landings, which is reflected in the benthic habitats analysis for the central California region (Figure 3, Figure 4).

Spiny lobster brought in more than $10 million annually during the past five years as the highest per unit value fishery in California (Table 2). Spot prawn, the second most valuable fishery per kilogram, is a small-volume, high-value fishery that has brought in an average $3.4 million for each of the past five years. The third most valuable fishery per kilogram is the sea hare fishery, which has brought in less than $50,000 per year for the past five years; the price per kilogram, however, is very high. Sea hares are fished primarily for experimental use in neurological research (Medina et al. 2001), as well as for the aquarium trade.

Emerging fisheries in the 1990s have also contributed to the rise in invertebrate fisheries in California (Figure 5c). Over the recent five years (2008–2012), warty and giant red sea cucumber fisheries annually averaged more than $1.9 million, more than the average value of white seabass (*Atractoscion nobilis*), albacore tuna (*Thunnus alalunga*), or petrale sole (*Eopsetta jordani)*. Giant red sea cucumbers are fished primarily by trawl, while the warty sea cucumbers are taken by commercial divers. The average price for sea cucumbers has also increased more than four-fold in the past decade, starting at $2/kg in 2003 and increasing to $8/kg in 2012, an increase that has been fueled by escalating demand from Asia. Aside from a limited entry program, there currently are no management measures in place for this data-poor fishery. Kellet's whelk is primarily a bycatch fishery in lobster and crab traps, with a small targeted dive fishery. Following the start of the fishery during the mid-1990s, landings grew substantially to a peak of 86.7 t in 2006. From the start of the fishery to 2006, an estimated 2.6 million whelk have been taken (approximately 150 g/whelk; L. Rogers-Bennett, unpublished data). By 2010, there was concern for the sustainability of the whelk fishery and a total allowable catch (TAC) of 45 t was imposed in 2012 by the California Fish and Game Commission. The most recent (2013–2014) landings finished at 38 t, just under the new TAC.

Invertebrate fisheries management and fishing down food webs.—There has been an increase in lower trophic level species comprising California's top fisheries (Figure 6), consistent with the hypothesis of fishing down marine food webs (Pauly et al. 1998). Crab and lobster are scavengers holding lower trophic positions than some of the species that dominated California landings in the early 1980s, such as salmon and tunas (both of which are top level predators). Red sea urchins are herbivores holding a lower trophic position. One of the newer invertebrate fisheries targets the sea cucumber, a detritivore that occupies a lower trophic position than most fin-fish. Having a low position in the trophic level does not appear to make fisheries resistant to collapse (Pinsky et al. 2011). For example, the sardine fishery in California suffered one of the most famous fishery collapses in history (Radovich 1982), and that species is a not a predator but a planktivore. Similarly, abalone are herbivores, but the fisheries south of San Francisco are now closed due to overfishing (Hobday et al. 2001, Rogers-Bennett et al. 2002).

The question arises, how will we sustainably manage California invertebrate fisheries, especially in the face of variable ocean conditions? We know that sea surface temperatures are a major influence on California's top fisheries. Catches of market squid, for example, fluctuate dramatically with environmental conditions, with radically reduced catches in warm water years such as 1982–1983, 1992, and 1998 (Zeidberg et al. 2006, Koslow and Allen 2011). Similarly, the new recruits of many commercially important invertebrate species, such as spiny lobster, also appear to show trends in recruitment associated with oceanographic conditions (Koslow et al. 2012) such as the Pacific Decadal Oscillation (Mantua et al. 1997). For example, 2004 was one of the best lobster phyllosoma seasons in the past 60 years (Koslow et al. 2012). In contrast, species such as Dungeness crab appear to have increased productivity during cold water years, suggesting good years for some species of invertebrates may not be good years for others. Invertebrates are famous for having large temporal fluctuations in productivity (driven by oceanographic processes) and this may need to be taken into consideration when future fishery management strategies are developed. Even small changes in mortality rates of early life history stages of fished species can translate into large changes in their population dynamics (Koslow 1992). So, what are some options for managing invertebrate fisheries given wide fluctuations in populations and varying ocean conditions?

One option would be to manage the fishery assuming the productivity of an "average" year, knowing we would overfish in some years and "underfish" in other years (Parma 2002). Such a fixed exploitation rate strategy (Walters and Parma 1996) may work with long-lived invertebrates but may not be sustainable for short-lived species, when just a few years of overfishing during bad years could have serious negative population consequences. Short-lived species, while they may bounce back from overfishing faster than long-lived species, may have more unstable population dynamics (Charnov 1993). Therefore, it may be necessary to manage species based on their population dynamics. However, there appears to be little evidence that the species comprising California's top fisheries have similar population dynamics or respond to ocean conditions in the same way. This may pose new challenges for ecosystem-based management if, for example, the productivities of squid (which do poorly in warm years) and lobster (which do well in warm years) differ in the same year. Another option would be to incorporate what is known about the impacts of temperature on productivity into harvest control rules, as is done in California for Pacific sardine (PFMC 2014). Temperature data can also be used as recruitment proxies in models examining productivity (White and Rogers-Bennett 2010).

There have been a number of arguments for adaptive management (fishery experiments) to learn from the application of management strategies and to apply these lessons in setting sustainable fishing levels (Walters and Hilborn 1978). In the case of marine invertebrates in California, monitoring the density of adult stocks, coupled with adaptive management, could be one way forward. This innovative strategy is now employed in northern California to manage the recreational red abalone (*Haliotis rufescens*) fishery (Kashiwada and Taniguchi 2007). Knowing the metapopulation dynamics of larval production coupled with the status of adult stocks at the local level could be another successful approach. In this way, adaptive management could be useful despite the suite of problems associated with invertebrate stock-recruit relationships and violations in assumptions of equilibrium traditionally used when setting maximum sustainable yields. Whatever fishery management methods are used, the continued tracking of fisheries landings (fishery-dependent data), particularly of top invertebrate fisheries, will be key to the success of sustainably managing invertebrate fisheries in California and the broader eastern Pacific Ocean.

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