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Forecasting the legacy of offshore oil and gas platforms on fish community structure and productivity

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Abstract. There are currently thousands of offshore platforms in place for oil and gas extraction worldwide, and decommissioning efforts over the next three decades are estimated to cost more than US$200 billion. As platforms reach the end of their useful lifetime, operators and regulatory agencies will assess the environmental impact of potential decommissioning strategies. Among the many factors that will be weighed in preparation for these major economic and engineering challenges is the fate of the fish and invertebrate communities that inhabit the structures underwater. Offshore platforms act as inadvertent artificial reefs, and some are recognized among the most productive fish habitats in the global oceans. We present a model for forecasting changes to fish communities surrounding offshore installations following a series of decommissioning alternatives. Using 24 platforms off southern California, we estimate fish biomass and somatic production under three possible decommissioning scenarios: leave in place, partial removal at 26-m depth, and complete removal of the platform and underlying shell mound. We used fish density and size data from scuba and submersible surveys of the platforms from 1995–2013 to estimate biomass and annual somatic production. Bottom trawl surveys were used to characterize future fish assemblages at platform sites under the complete-removal decommissioning scenario. Based on a conservatively modeled extrapolation of the survey data, we found that complete removal of a platform resulted in 95% or more reduction in the average fish biomass and annual somatic production at the site, while partial removal resulted in far smaller losses, averaging 10% or less. In the event that all surveyed platforms are completely removed, we estimated a total loss of more than 28,000 kg of fish biomass in the Southern California Bight. Platform habitats, which attract reef-dwelling fish species, had minimal overlap in community composition with the surrounding soft-bottom habitat. To best serve the wide range of stakeholder interests, the site-specific biomass, productivity and species composition information provided in this study should be incorporated into strategic decommissioning planning. This approach could be used as a model for informing "rigs to reefs" discussions occurring worldwide.

Key words: artificial reef; decision-making; decommissioning; ecological forecasting; offshore platform; rigs to reefs; Sebastes.

Introduction

Offshore drilling for oil and gas is a major human use of the oceans and thousands of oil and gas platforms have been installed on the continental shelves worldwide (Parente et al. 2006). As the underlying hydrocarbon reservoirs are depleted and equipment ages, platform drilling operations become less profitable and are shut down. In this decommissioning process, wells are capped, infrastructure is removed, and the seafloor may be cleared of any obstructions (Schroeder and Love 2004). More than 2,600 oil and gas installations are projected to be decommissioned within the next few decades, with costs worldwide from 2010–2040 estimated to reach US$210 billion (IHS Markit 2016). Environmental impacts associated with platform demolition and removal include a substantial carbon footprint, waste generation and potential release of contaminants (Schroeder and Love 2004, Fowler et al. 2014). The underwater structures also are habitats for marine life, the majority of which is destroyed in the removal process (Basavalinganadoddi and Mount 2004).

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The Rigs to Reefs decommissioning alternative, where all or a portion of the platform is left in the ocean to continue its life as an artificial reef, has been proposed to reduce some of these economic and environmental costs (Reggio 1987, Schroeder and Love 2004, Macreadie et al. 2011, Bull and Love 2019). This approach also has drawbacks, however, such as reducing workable area for commercial fishermen (de Wit 2001), and creating ongoing liability for the agency managing the artificial reef (Jagerroos and Krause 2016). Public sentiment on artificial reef conversion is mixed, with some groups preferring sites to be returned to a pristine state (Jørgensen 2012, Olsen 2016). This decision is multifaceted, and stakeholders have different environmental, economic, and political goals. Ultimately, the decision to pursue an alternative to total structure removal is made by the presiding regulatory agency and the platform operator, in accordance with current laws and international agreements (Osmundsen and Tveterås 2003, Parente et al. 2006, Fowler et al. 2018). Complete removal continues to be the default decommissioning mandate in the United States (Bull and Love 2019), Australia (Techera and Chandler 2015), and Europe (Fowler et al. 2018). However, a panel of environmental experts concluded that platform decommissioning decisions should be made on a case-by-case basis, accounting for variations in platform structure, local environment, and ecology, to achieve the best possible environmental outcomes (Fowler et al. 2018).

There are currently 27 oil and gas platforms off the coast of southern California (Table 1). In part due to their significant vertical extent and position in offshore currents, these artificial reefs are highly productive marine ecosystems (Page 1986, Page and Hubbard 1987, Claisse et al. 2014, Santora et al. 2017), and may contribute to the recovery of commercially important reef-dwelling fish species (Love et al., 2005, 2006). For example, larval production of two overfished species, cowcod (*Sebastes levis*) and boccacio (*Sebastes paucispinis*), is proportionately higher on platforms than natural reefs due to the higher densities and larger sizes of spawning adults (Love and Schroeder 2006, Claisse et al. 2019). Seven California platforms were decommissioned in the 1980s and 1990s, with removal of most of the platform structure (Manago and Williamson 1998, Bernstein et al. 2010). The cost and negative impacts of these projects, such as air quality issues, recycling and waste generation, and impacts on marine life, have sparked interest in exploring decommissioning alternatives for the remaining platforms (Schroeder and Love 2004, Macreadie et al. 2011, Pondella et al. 2015). This has become a pressing discussion since several platforms are expected to go through the decommissioning process in the coming years (Bureau of Safety and Environmental Enforcement 2018, 2019, Bull and Love 2019).

Three main options are under consideration for decommissioning the remaining California platforms: leave in place, partial removal, or complete removal. In the leave-in-place alternative, the wells are capped but the entire underwater portion of the platform is preserved as an artificial reef. Partial removal involves the removal of all platform components near the surface that present a navigational hazard to ships (Stephan et al. 1990, Schroeder and Love 2004). In the complete-removal scenario, the platform is severed from the seafloor using explosives or mechanical cutting, removed piecemeal, and recycled, reused, or discarded (Schroeder and Love 2004, Basavalinganadoddi and Mount 2004). The use of explosives and removal of the underwater hard substrate results in the destruction of fishes and invertebrates associated with the structure (Gitschlag et al. 2000, Schroeder and Love 2004), and can pose a hazard to marine mammals and turtles (Klima et al. 1988). Due to the diverse and productive marine communities that can be associated with platforms, California Assembly Bill 2503 states that any analysis evaluating alternatives to complete structure removal should include the "contribution of the proposed structure to protection and productivity of fish and other marine life" (California Marine Resources Legacy Act 2010).

Here, we use fish community data from platforms and nearby soft-bottom habitats to examine the ecological impacts of a range of decommissioning scenarios on California platforms. We assessed fish biomass and somatic production on 24 platforms and forecasted changes to the fish community biomass and production on each platform under the three alternative decommissioning scenarios: leave in place, partial removal to a depth of 26 m, and complete structure removal. Predictions of fish biomass and productivity on platforms under the partial-removal and leave-in-place scenarios were based on scuba diver and manned submersible surveys conducted from 1995–2013. Only the outer part of each platform was surveyed, and we estimated total platform-associated fish communities in three different ways, first using only the survey data, and then scaling it up to the portions of the water column that were not surveyed, using two alternative approaches.

To forecast the fish communities that would inhabit the platform footprint under the complete-removal scenario, we used bottom trawl surveys conducted near the platforms to forecast the fish communities that would inhabit the platform footprint upon reversion to soft bottom, building upon previous work that considered only the loss of platform habitat (Claisse et al. 2015, Pondella et al. 2015). Consideration of both habitat loss and gain under the three decommissioning scenarios reduces the risk of overestimating fish loss following structure removal and presents a more accurate forecast

TABLE 1. Pacific offshore oil and gas platform structure.

Platform	Region	Jurisdiction	Year installed	Base depth (m)	No. Midwater beams	Jacket footprint (m^2)	Jacket volume (m^3)	Shell mound area (m^2)
A	East SB Channel	Federal	1968	58	4	1,930	75,653	3,382
B	East SB Channel	Federal	1968	58	5	1,930	75,330	3,122
C	East SB Channel	Federal	1977	58	5	1,930	75,330	3,493
EDITH	Orange County	Federal	1983	49	2	2,879	112,147	NA
ELLEN	Orange County	Federal	1980	80	3	2,511	131,841	NA
ELLY	Orange County	Federal	1980	77	3	2,949	140,382	NA
EMMY†	Orange County	State	1963	14	NA	669	9,360	NA
ESTHER†	Orange County	State	1985	10.7	NA	669	7,154	NA
EUREKA	Orange County	Federal	1984	212	9	4,635	563,814	NA
EVA†	Orange County	State	1964	17	NA	669	11,366	NA
GAIL	East SB Channel	Federal	1987	224	9	5,327	671,776	655
GILDA	East SB Channel	Federal	1981	62	3	2,342	97,386	18,290
GINA	East SB Channel	Federal	1980	29	1	561	11,305	2,926
GRACE	East SB Channel	Federal	1979	96	4	3,090	199,728	22,754
HABITAT	East SB Channel	Federal	1981	88	4	2,284	119,889	4560
HARMONY	West SB Channel	Federal	1989	363	7	10,606	1,659,349	NA
HARVEST	Pt. Conception	Federal	1985	205	7	5,859	683,741	NA
HENRY	East SB Channel	Federal	1979	52	3	1,505	77,220	4,560
HERITAGE	West SB Channel	Federal	1989	326	3	10,606	1,490,214	NA
HERMOSA	Pt. Conception	Federal	1985	183	8	5,142	599,639	642
HIDALGO	Pt. Conception	Federal	1986	130	5	4,154	366,288	0
HILLHOUSE	East SB Channel	Federal	1969	58	3	1,960	76,662	4,515
HOGAN	East SB Channel	Federal	1967	47	3	1,435	67,868	4,932
HOLLY	West SB Channel	State	1966	64	4	1,728	69,120	NA
HONDO	West SB Channel	Federal	1976	255	7	4,649	587,722	1,821
HOUCHIN	East SB Channel	Federal	1968	49	3	1,435	70,756	5,721
IRENE	Pt. Conception	Federal	1985	73	3	2,633	123,884	13,484

Note: NA, not applicable.
†No fish surveys performed.

of overall changes to fish abundance, biomass, and somatic production. Since oil and gas platforms provide considerable vertical habitat to accommodate fish relative to the surrounding soft bottom, we predicted that structure removal would generally result in an overall net loss of fish biomass and somatic production.

METHODS

Fish surveys

There are several underwater components of an offshore oil and gas platform that provide structural habitat for fish (Schroeder and Love 2004). Each platform consists of a series of large-diameter vertical conductor pipes that span the entire water column to transport the drills and the fossil fuels between the seafloor and the surface. The jacket is a rectangular steel lattice of smaller pipes that surround and support the conductors as well as the platform deck at the surface. Bivalves that grow on the jacket and conductors fall to the seafloor below and form a shell mound that adds additional structural habitat to the site.

Fishes around platforms were visually surveyed by scuba divers, manned submersible, or remotely operated vehicle (ROV) around 24 southern California platforms from 1995 to 2013 (Fig. 1; Love et al. 2017*a,b*). Belt transects 2 m high and 2 m wide were conducted on the shell mound around the platform, along the perimeter of the platform base, and along each major external horizontal jacket cross beam throughout the midwaters. Fish were counted, identified to species when possible, and total length was estimated to the nearest 5-cm increment. See Appendix S1 for additional detail on survey protocol and effort around platforms.

Under the complete-removal decommissioning scenario, all of the platform structure and the shell mound will be removed, causing the habitat to revert back to soft bottom. Estimation of fish biomass and somatic production in the complete-removal scenario was based on data from bottom trawl surveys of fish communities over surrounding soft substrate. Data from two surveys were used: the NOAA West Coast Groundfish Bottom Trawl survey from 2003 to 2015 (West Coast Groundfish Bottom Trawl Survey 2017, Keller et al. 2017) and the Southern California Coastal Water Research Project

(SCCWRP) Southern California Bight Regional Survey trawls conducted in 2003, 2008 and 2013 (Southern California Bight Regional Survey 2017). Trawls that occurred within a 30 km radius and at an average bottom depth within 25 m of the base depth of an individual platform were associated with that site and used in the complete-removal fish community forecast. Trawl survey effort was variable, for example, SCCWRP trawls were not conducted near the most northwestern platforms in the Point Conception region, and WCGBT trawls were rare within a 25-m depth range of the shallowest platforms (Appendix S1: Table S1).

The NOAA West Coast Groundfish Bottom Trawl surveys have been conducted biannually with consistent methodologies since 2003 (Keller et al. 2008, 2017). An Aberdeen-type trawl with 31.7-m footrope and cod end mesh size of 14 cm was used (Millar 1992, Dickson 1993). Minimum bottom depth was 55 m, limiting the usefulness of this survey for the shallowest platforms. Fish were sorted into taxonomic groups and weighed together. Individual lengths were only recorded for a subsample of the catch. SCCWRP bottom trawl surveys used semi-balloon otter trawls with an 8.8-m footrope and cod end mesh size of 1.25 cm (Southern California Bight Regional Survey 2017, Allen et al. 2011) and were conducted nearshore with high sampling frequency near the shallowest platforms. Length of all fish was measured to the nearest cm.

Abundance, biomass, and somatic production metrics

Fish abundance, biomass, and somatic production were calculated and compared for both platform visual surveys and benthic trawl surveys. Comparisons of fish community composition between habitat types are presented at the genus level for ease of interpretation. In platform surveys, the biomass of individual fish was estimated using length–mass relationships from the literature (see Claisse et al. 2014). In trawl surveys, fish were weighed directly. Somatic production was defined as the expected annual mass increase of individual fish that were estimated to survive for at least one year, derived from von Bertalanffy growth functions and survivorship functions (Gislason et al. 2010, Haddon 2011). For platform and SCCWRP surveys, individual fish lengths were recorded and used to estimate somatic production in the following year. Individual fish lengths were not measured in the WCGBT surveys, therefore somatic production was derived from the mean weight per species for each trawl. A detailed explanation of the methods for calculating biomass and somatic production is provided in Appendix S1.

A linear model was built to test the effects of site, year, depth, and habitat type (platform midwater, platform base, platform shell mound, WCGBT survey, and SCCWRP survey) on fish density (Appendix S1). Both species richness and the Shannon-Weiner diversity index

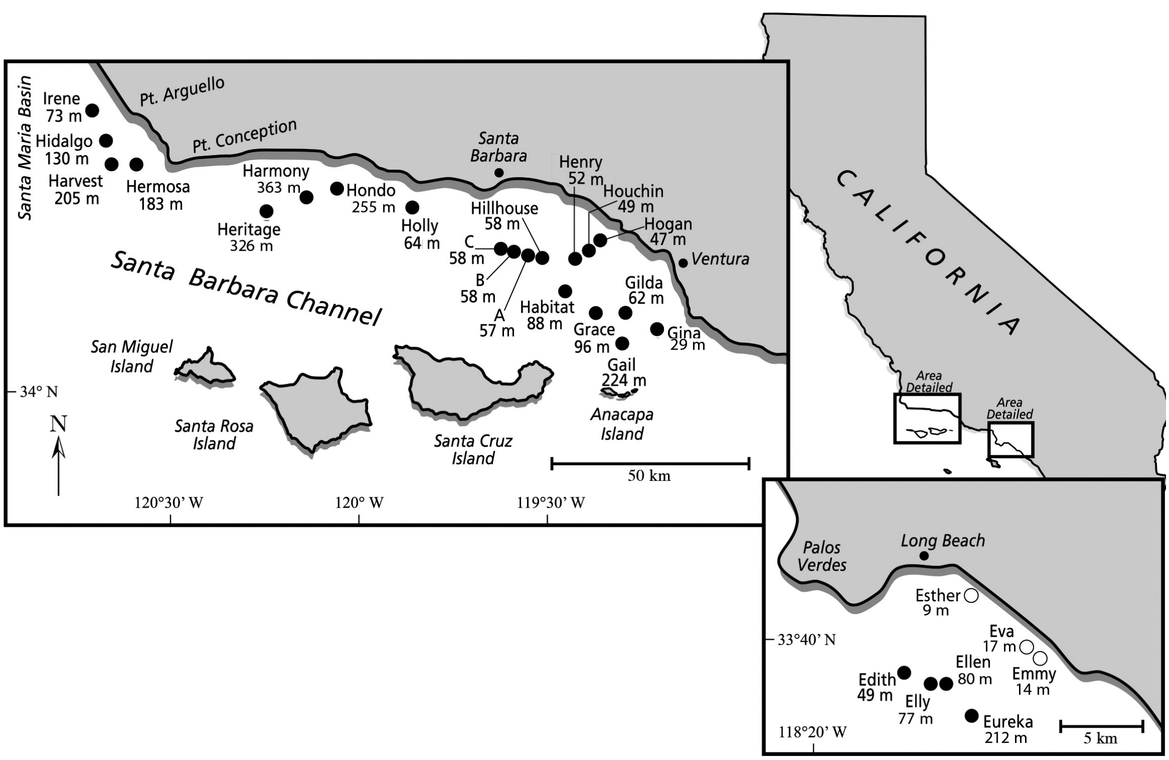

FIG. 1. Map showing the names, locations, and seafloor depths (m) of the 27 Southern California offshore oil and gas platforms. Solid circles indicate platform sites that have been surveyed and included in this study.

were calculated and compared across each of the five habitat types. To examine the effects of site, year, depth, and habitat type on species composition, a Bray-Curtis dissimilarity matrix was calculated from species-specific densities (fish/m^2) at each survey transect conducted on the platforms or soft bottom. Fish densities were first transformed to the fourth root to avoid overrepresentation by species with very high observation counts, similar to previous studies (Love et al. 2019). A two-dimensional nonmetric multidimensional scaling (nMDS) ordination plot was created to visualize the similarity between observed fish communities. Permutational multivariate analysis of variance was performed on the Bray-Curtis distance matrix using 999 permutations to test the effects of site, habitat type and observation year as categorical variables and sampling depth as a continuous variable on the assemblages observed (Oksanen et al. 2019, R Core Team 2019). Multivariate dispersion was tested to determine whether variance was homogenous between groups among the dependent variables.

Scaling fish metrics up to total platform habitat

The underwater region associated with a single platform provides several unique habitats that may harbor different species and sizes of fishes (Love et al. 2000, 2003, 2019). To account for the community variation between different portions of a single platform, each platform site was divided into several habitat types: the shell mound, the jacket base, and a series of depth strata in the jacket midwater corresponding to the positions of every major horizontal beam on the jacket. For each transect surveyed, we calculated species-specific fish abundance, and volumetric densities of biomass and somatic production. These metrics were averaged across all surveys to characterize the difference in abundance, biomass and somatic production between habitat type. Then to characterize site-specific variations in the fish community to inform decommissioning, we calculated the average fish abundance, biomass and somatic production densities at each platform across all surveys conducted within each habitat type. The average fish abundance, biomass, and somatic production estimated at each midwater depth strata were then summed at each platform to estimate midwater habitat totals.

Since only a small portion of each habitat type is surveyed on each platform, we present three different methods for applying the surveyed volumetric fish densities to characterize the total water column somatic production over each platform footprint. These methods are based on three alternative assumptions about how much of the habitat can be characterized by the surveyed fish densities. The three methods are (1) beams only, including only fish in surveyed regions; (2) beam slices, extrapolating surveys of horizontal beams into the interior of the platform but only within the 2 m high vertical strata included in the surveys; and (3) total jacket, extrapolating survey results to the entire volume within the jacket structure (Fig. 2, see Appendix S1 for detail).

Decommissioning scenarios

To inform the future decommissioning process, we predicted fish community biomass and somatic production under three potential platform decommissioning scenarios: leave in place, partial removal, and complete removal of the platform and shell mound. Although there are no defined requirements on the portion of structure that must be removed in the partial-removal scenario, for the sake of this study, we assumed removal of all structure above a depth of 26 m, which would eliminate the necessity for marking by a lighted buoy based on U.S. Coast Guard guidelines (Stephan et al. 1990, Schroeder and Love 2004). We did not consider potential future environmental or fishing effects on fish populations and community structure in this study, and assumed fish densities from the surveys and trawls represent future populations. The partial-removal estimates are identical to the leave in place, except all fish from depths shallower than 26 m were removed.

In the complete-removal scenario, we assumed that the fish assemblage will revert back to a soft-bottom ecosystem, approximated using data from trawl surveys conducted over soft-bottom habitats near each platform site. Biological metrics reflect estimates derived from either SCCWRP or WCGBT when data from only one of the surveys was available but, in most cases, SCCWRP and WCGBT estimates were averaged to estimate the complete-removal scenario at each platform (Appendix S1: Table S1). Soft-bottom densities were calculated per benthic area swept by the trawl. These densities were then scaled to the total footprint area of the platform jacket and surrounding shell mound (Table 1).

Results

Fish densities and taxa found on platforms and soft bottom

Across all platforms and survey dates for the three habitat types, average fish count densities were typically highest at the jacket base, with a mean density of 1.65 ± 0.20 fish/m^3 (mean ± SE; Fig. 3; Appendix S1: Table S2). Average fish densities in the midwater portion of the jackets and shell mounds were similar, 0.79 ± 0.10 fish/m^3 and 0.81 ± 0.20 fish/m^3, respectively (Fig. 3). Rockfishes (genus *Sebastes*) dominated the platform habitats below 26 m depth, including the platform base and shell mound (Fig. 4). The most common rockfish species observed on the platforms were halfbanded (*Sebastes semicinctus*), squarespot (*Sebastes hopkinsi*), and widow (*Sebastes entomelas*) rockfishes. The upper 26 m of the platform jackets were typically dominated by blacksmith (*Chromis punctipinnis*; Fig. 4).

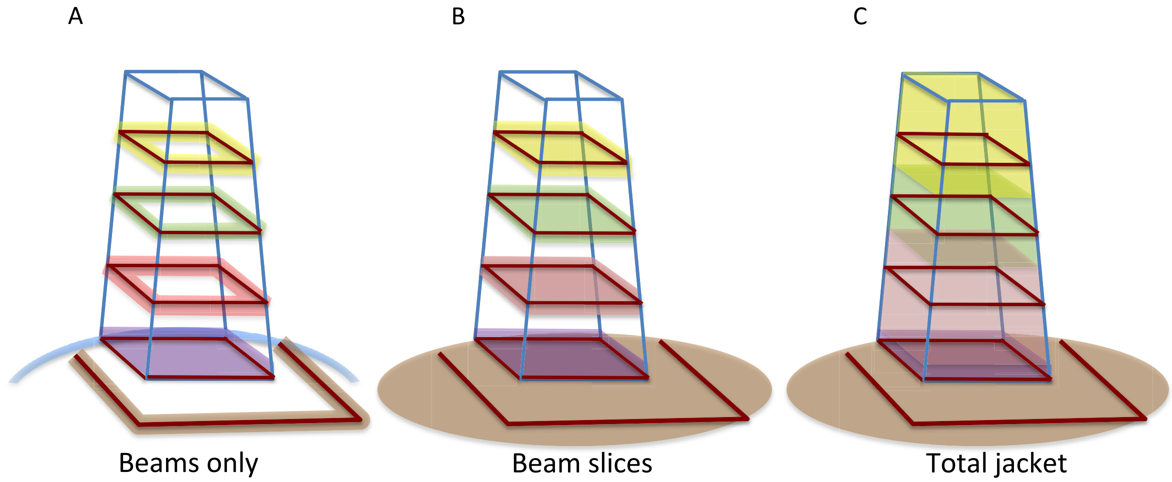

FIG. 2. Schematics show three separate methods for scaling up platform survey fish densities on a simplified platform jacket. Colored polygons indicate the volume associated with each surveyed habitat: midwater beams at three depth levels (yellow, green, pink), the rig base (purple), and the shell mound (brown). (A) The beams-only method accounts only for fish along the beam, base, and shell mound survey transects, with 2-m transect widths and heights. (B) In the beam-slices method, fish densities measured along each beam are scaled up to a 2 m high beam slice running through the middle of the jacket. Shell mound densities are scaled up to the total shell mound area. (C) In the total jacket method, the total volume of the jacket is broken into a stack of truncated pyramids bounded by the legs of the jacket, with horizontal boundaries positioned halfway between adjacent midwater beams. Fish densities measured along each beam are scaled up to the volume of the truncated pyramid intersected by that beam. Shell mound densities are scaled up to the total shell mound area. [Color figure can be viewed at wileyonlinelibrary.com]

Fish densities estimated from both soft-bottom trawl surveys were much lower than the average density observed on any of the three platform habitats (Fig. 3; Appendix S1: Table S2). The mean numerical density across all SCCWRP surveys included in this study was 0.03 ± 0.003 fish/m^3 and the mean density across WCGBT surveys was 0.05 ± 0.009 fish/m^3. Taxonomic compositions of the fishes recorded in the soft-bottom trawl surveys differed between the SCCWRP and WCGBT surveys (Fig. 4). The most common species observed in SCCWRP trawls were speckled sanddab (*Citharichthys stigmaeus*), Pacific sanddab (*Citharichthys sordidus*), and California lizardfish (*Synodus lucioceps*). The most common species observed in WCGBT surveys were pink seaperch (*Zalembius rosaceus*), slender sole (*Lyopsetta exilis*), and shortbelly, splitnose, and stripetail rockfish (*Sebastes jordani*, *S. diploproa*, and *S. sax cola*, respectively). There was very little overlap between the fish species observed in the soft-bottom surveys and the platform surveys. Although rockfish (*Sebastes*) were still moderately common in the two soft-bottom trawl survey types, they were primarily species that prefer sandy and muddy demersal habitats, rather than the reef-dwelling rockfishes that dominate the platforms.

Variation in fish species assemblage at each survey was driven primarily by habitat type (Fig. 5). The nMDS ordination plot revealed that the SCCWRP and WCGBT soft-bottom communities are similarly structured. In a separate cluster, the three platform habitat types, the midwater, base, and shell mound, also exhibited considerable overlap in community structure. The two benthic habitat types surveyed on platforms, the base and shell mound, were more similar to the soft-bottom species compositions than the midwater platform communities, however, there was still no overlap between the benthic platform communities and the soft bottom. The PERMANOVA analysis indicated that site, habitat type, year, and depth were all significant predictors of the species assemblages observed at each survey, with habitat type having the largest effect on community structure (Table 2). Variances among the tested groups site, habitat type, year, and depth were not homogenous, therefore at least a portion of the effect of these variables on community composition is driven by the variance within groups.

Differences in diversity between habitat types were statistically significant, with the lowest species richness in the platform midwater habitat (Appendix S1: Table S3). Both species richness and the Shannon-Weiner diversity index were more similar among the remaining four habitat types, the platform base, shell mound, SCCWRP trawls and WCGBT trawls, all of which are on or near the benthos (Appendix S1: Fig. S2).

Platform biomass and somatic production estimates

Biomass estimates of fishes within the survey areas (beam only) ranged from 15.8 ± 5.0 kg on Platform Henry to 577 ± 54 kg on Platform Elly (Table 3). Somatic production estimates within the survey areas (beam only) ranged from 3.47 kg/yr (SE unavailable because site was surveyed only once) on Platform

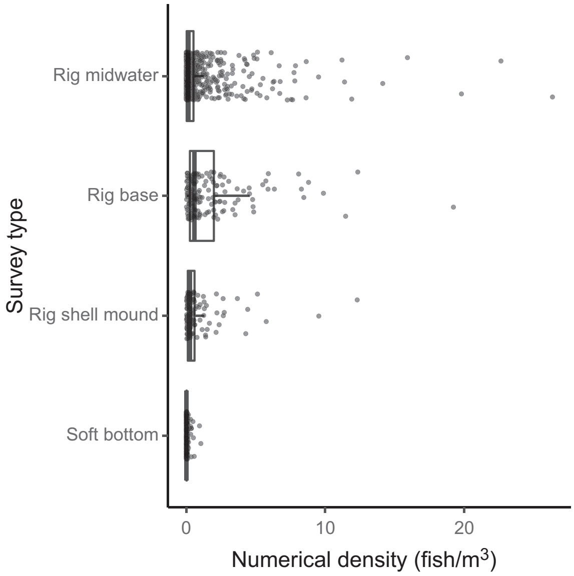

FIG. 3. Box plots of fish density (number of fish/m^3) at each survey by habitat. Southern California Coastal Water Research Project (SCCWRP) trawl surveys and West Coast Groundfish Bottom Trawl (WCGBT) surveys of soft-bottom fish densities are combined. Only trawls that were conducted within 30 km of a platform and within 25 m depth range of a platform base are included. Box plot midlines show the median, box edges show the first and third quartiles, and whiskers extend to the furthest values up to 1.5 x the interquartile range.

Houchin to 100 ± 21 kg/yr on Platform Grace (Table 3). These estimates only include fishes that were found within the surveyed habitat directly adjacent to the horizontal beam, which is extremely limited relative to the total volume of water occupied by the platform structure.

Using the two approaches for scaling up the survey data resulted in correspondingly higher biomass and somatic production estimates. For the more conservative beam slices method, total platform biomass ranged from 93.4 ± 11 kg on Platform Gina to 4,440 ± 610 kg on Platform Grace. Somatic production ranged from 15.0 ± 1.7 kg/yr on Platform Gina to 741 ± 140 kg/yr on Platform Grace (Table 3). Using the more liberal total jacket volume scaling method, total platform biomass ranged from 316 ± 150 kg on Platform Henry to 32,600 ± 3,300 kg on Platform Eureka. Somatic production ranged from 80.9 kg/yr (SE unavailable because site was surveyed only once) on Platform Houchin to 5,000 ± 1,200 kg/yr on Platform Grace (Table 3).

Biomass and somatic production forecasts under partial- and complete-removal scenarios

The potential impacts of decommissioning on platform fish communities are demonstrated by forecasting changes in the fish community in the partial and full removal decommissioning scenarios relative to the leave in place scenario. Forecasts are presented using the moderate beams slices scaling method; results from the other two scaling methods are included in Data S1.

To forecast the partial-removal decommissioning scenario, we assumed the loss of all fishes within the upper 26 m of the water column. The partial-removal scenario resulted in an average loss of 10% of the fish biomass across all of the surveyed platforms, but varied considerably, ranging from 0% loss on platforms Grace, Harmony, Heritage, Hondo, and Irene to 44% biomass loss on Platform Gina (Table 4). The partial-removal scenario resulted in an estimated average loss of 8% of fish somatic production across all of the surveyed platforms, ranging from 0% loss on platforms Grace, Harmony, Heritage, Hondo, and Irene to 48% somatic production loss on Platform Gina (Table 4). The projected loss is 0% on some platforms because there are no major horizontal jacket beams that occur within the upper 26 m of the water column at those sites. Platform Gina, as well as platforms Edith, Henry, and Hogan, have relatively high projected losses in the fish assemblage relative to the other platforms because these are the shallowest platforms in the study (Platform Gina sits at a depth of 29 m) and the upper 26 m includes at least one-half of the horizontal cross beams at these sites (Table 1). For all 24 surveyed platforms, the majority of the fish assemblage was retained following the removal of rig structure above 26 m depth.

Soft-bottom trawl surveys were used to forecast change in fish biomass and somatic production in the complete-removal scenario. We estimated that the complete-removal scenario would result in an average loss of 96% of the fish biomass across all of the surveyed platforms, ranging from 83% loss on Platform Heritage to at least a 98% loss on 15 of the surveyed platform sites (Table 4). Similarly, complete removal will result in an average loss of 95% of the somatic production across all surveyed platforms, ranging from 66% loss on Platform Heritage to at least a 98% loss on 14 of the platforms surveyed (Table 4). Losses in somatic production on the large platforms Heritage and Harmony are smaller because the large footprint of these two jackets (Table 1) will result in a substantially larger reclamation of soft-bottom habitat relative to the other platform sites.

To illustrate the scale of the impact that each decommissioning alternative might have for reef fish offshore of southern California, we aggregated the total fish biomass and somatic production across all 24 platforms included in this study under the three decommissioning scenarios (Fig. 6). In this example, we assume that the same decommissioning alternative is applied to all 24 platform sites and we use the beam slices approach to estimate metrics. If the complete underwater structure at all 24 sites is left in place, the platform-associated habitats will support a total of 29,171 ± 1,741 kg of fish biomass, and an annual somatic production of 4,772 ± 374 kg/yr. If the top 26 m of each platform jacket is removed, but the jacket and shell mound materials below 26 m is retained, the platform-associated habitats

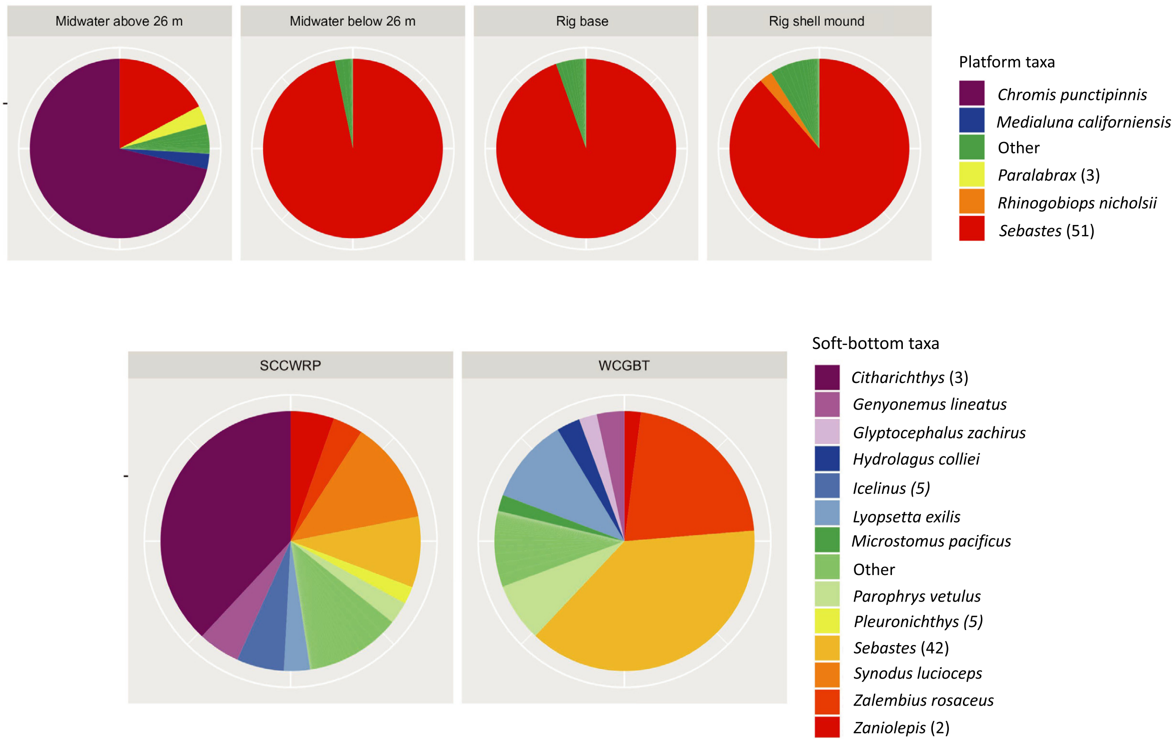

FIG. 4. Abundance of fish by taxonomic group in all surveys of platforms (top row) and soft-bottom trawls (bottom row). Taxonomic groups are categorized by genera; if only one species in the genus was observed, the species name is provided, otherwise the number of species represented by that genus is provided in parenthesis. Platform taxonomic abundance charts are broken into four distinct habitats: jacket midwater surveys above a 26-m depth, jacket midwater surveys below a 26-m depth, jacket base surveys, and shell mound surveys. Soft-bottom taxonomic abundance charts are separated into the two trawl survey methods: Southern California Coastal Water Research Project (SCCWRP) trawl surveys and West Coast Groundfish Bottom Trawl (WCGBT) surveys. Fish taxa representing <2% of the total fish abundance for each distinct habitat type or method are aggregated into Other. [Color figure can be viewed at wileyonlinelibrary.com]

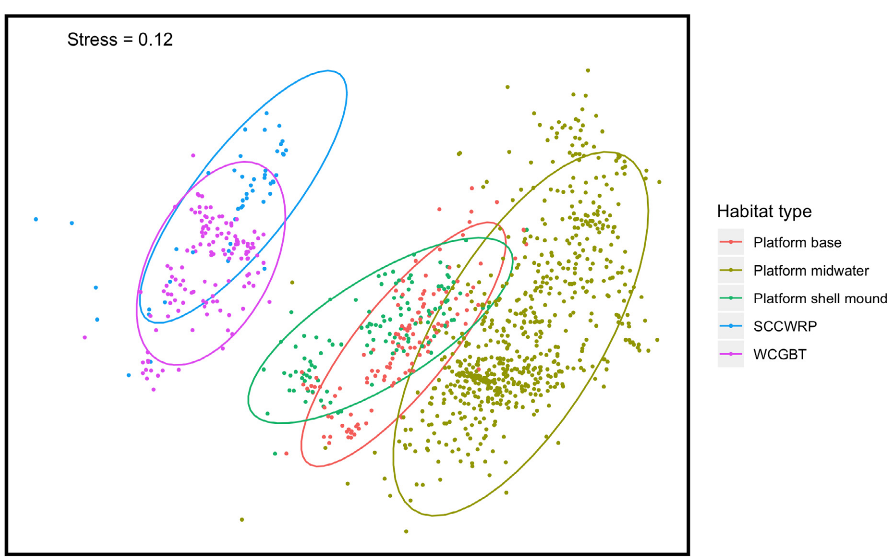

FIG. 5. Two-dimensional nonmetric dimensionless scaling (nMDS) ordination plot demonstrating the two dominant modes of variability in a Bray-Curtis dissimilarity matrix constructed from fourth-root-transformed fish communities surveyed along platforms and soft-bottom habitats. Colors indicate the habitat type surveyed and ellipses represent 95% confidence intervals around the centroid of each habitat type. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. Permutational analysis of variance (PERMANOVA) model testing the effects of site, habitat type, observation year, and depth on fish community composition.

Effect	df	Pseudo-F	R^2	P
Site	26	12.53	0.17	0.001
Habitat type	4	111.02	0.23	0.001
Year	20	4.63	0.05	0.001
Depth	1	45.15	0.02	0.001

Note: PERMANOVA was performed on a Bray-Curtis dissimilarity matrix of fourth-root-transformed fish densities separated by species.

will support a total of 27,848 ± 1,737 kg of fish biomass, and an annual somatic production of 4,584 ± 374 kg/yr. If all 24 platform jackets and shell mounds are completely removed, the new soft-bottom habitat will support a total of 518 ± 29 kg of fish biomass, and an annual somatic production of 112 ± 6 kg/yr.

Discussion

The results of this study indicate that <5% of the fish biomass and somatic production associated with 24 California offshore oil and gas platform sites will be lost in the event of partial removal of the structures above a depth of 26 m. However, complete removal will result in a net loss of 98% of the biomass even though the artificial-reef-associated fish communities will be replaced with fish characteristic of the surrounding soft-bottom environments. Complete removal of the platform and shell mound of all 24 sites included in this study will result in a conservatively estimated net regional biomass loss of 28,653 kg of fish, with an additional loss of 4,659 kg/yr of annual somatic fish production (Fig. 6). To put these numbers into context, total commercial landings in Santa Barbara Harbor in 2017 consisted of 35,485 kg of rockfish, valued at US$357,106 (California Department of Fish and Wildlife 2018). This substantial fish loss following complete platform removal occurs because fish densities over soft-bottom are much lower than densities found in platform-associated habitats in southern California (Fig. 3).

Biological metrics vary substantially between the three methods developed in this study for applying the observed fish assemblages to the entire platform-associated habitat volumes. We recommend using estimates from the beam slices approach for general quantitative

Table 3. Biomass and somatic production estimates for each platform using the three methods: beams only, beam slices, and total jacket volume.

	Beams only				Beam slices				Total jacket volume			
	Biomass (kg)		Somatic Production (kg/yr)		Biomass (kg)		Somatic production (kg/yr)		Biomass (kg)		Somatic production (kg/yr)	
Platform	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
A	229	70	40	10	1,297	420	226	60	2,898	537	571	126
B	89	13	24	4	466	68	126	23	1,555	324	453	141
C	77	12	23	4	447	90	126	24	1,360	273	454	122
EDITH	198	32	31	6	938	136	148	33	5,549	1,228	673	114
ELLEN	403	74	53	21	2,020	400	270	117	18,986	7,058	3,766	2,166
ELLY	577	54	45	7	3,105	313	236	42	18,208	4,266	1,500	426
EUREKA	480	43	57	6	3,165	295	354	33	32,571	3,253	3,810	380
GAIL	296	30	49	5	2,359	266	393	42	4,097	379	857	112
GILDA	175	48	43	15	2,818	1,362	643	299	4,166	1,394	964	315
GINA	36	4	6	1	93	11	15	2	631	81	110	14
GRACE	506	81	100	21	4,443	613	741	137	17,859	4,054	4,998	1,231
HABITAT	60	11	18	4	343	55	100	21	2,828	836	979	348
HARMONY	34	NA	5	NA	351	NA	37	NA	2,508	NA	524	NA
HARVEST	118	18	27	5	730	106	159	29	7,293	1,220	1,723	332
HENRY	16	5	6	2	94	25	35	9	316	151	107	47
HERITAGE	30	NA	5	NA	353	NA	55	NA	10,731	NA	1,614	NA
HERMOSA	223	33	30	5	1,487	257	189	33	7,802	1,317	1,644	306
HIDALGO	154	16	22	3	1,079	118	144	16	3,242	509	609	141
HILLHOUSE	49	14	12	4	290	76	73	20	1,090	464	345	213
HOGAN	25	7	4	1	153	44	31	13	765	268	114	45
HOLLY	105	13	19	2	416	46	77	9	1,416	157	329	51
HONDO	162	45	22	5	891	219	129	29	14,312	4,107	2,098	505
HOUCHIN	17	NA	3	NA	175	NA	38	NA	430	NA	81	NA
IRENE	222	21	57	9	1,660	151	427	59	8,048	1,728	3,118	839

Notes: These values are used to simulate the leave-in-place decommissioning scenario. NA, not applicable.

TABLE 4. Platform-specific biomass and somatic production model estimates for each platform and the expected percent loss in biomass and somatic production under the scenarios of partial removal at 26 m and complete removal of platform infrastructure and shell mound.

	Biomass			Somatic production		
Platform	Biomass on platform (kg)	Loss with partial removal (%)	Loss with complete removal (%)	Production on platform (kg/yr)	Loss with partial removal (%)	Loss with complete removal (%)
A	1,297	0.08	0.99	226	0.06	0.99
B	466	0.14	0.98	126	0.06	0.99
C	447	0.03	0.98	126	0.01	0.98
EDITH	938	0.46	0.99	148	0.33	0.99
ELLEN	2,020	0.02	0.99	270	0.02	0.98
ELLY	3,105	0.03	0.99	236	0.04	0.98
EUREKA	3,165	0.05	0.99	354	0.09	0.98
GAIL	2,359	0.02	0.99	393	0.02	0.98
GILDA	2,818	0.03	0.99	643	0.02	0.99
GINA	93	0.44	0.98	15	0.48	0.96
GRACE	4,443	0.00	0.99	741	0.00	0.99
HABITAT	343	0.05	0.92	100	0.03	0.95
HARMONY	351	0.00	0.87	37	0.00	0.73
HARVEST	730	0.03	0.96	159	0.03	0.98
HENRY	94	0.28	0.90	35	0.22	0.94
HERITAGE	353	0.00	0.83	55	0.00	0.66
HERMOSA	1,487	0.01	0.98	189	0.02	0.98
HIDALGO	1,079	0.01	0.96	144	0.01	0.96
HILLHOUSE	290	0.12	0.96	73	0.09	0.96
HOGAN	153	0.37	0.96	31	0.07	0.95
HOLLY	416	0.08	0.99	77	0.11	0.98
HONDO	891	0.00	0.99	129	0.00	0.97
HOUCHIN	175	0.11	0.95	38	0.08	0.94
IRENE	1,660	0.00	0.99	427	0.00	0.99
Mean	1,215	0.10	0.96	199	0.08	0.95

Notes: The leave-in-place and partial-removal scenarios are based on the beam-slices method. The complete-removal scenarios are calculated using the biomass and somatic production estimates averaged between the Southern California Coastal Water Research Project (SCCWRP) and the West Coast Groundfish Bottom Trawl (WCGBT) surveys when both are available.

description of the platform-associated fish assemblage size because it provides a conservative estimate of the abundance, biomass and somatic production of fishes found at each platform. Since the space between beams is assumed to have no fish, this approach will result in an underestimate of fish present; however, the proportion of the total artificial reef that is not accounted for scales up with platform height since the spacing between major horizontal beams is wider at deeper platforms. The lower metrics provided in the beams-only approach are based on the assumption that there are no fish outside of the targeted survey volume. This approach is useful for quantifying the subset of the fish assemblage that has been directly observed and providing context for the gap between applied survey effort and a more idealized complete habitat monitoring program. However, the beams only approach does not produce a comprehensive assessment of the total fish community associated with the platform structure since it excludes fish in the jacket interior that may be present at densities higher than those observed on the external jacket beams. In a study of fish surveys in the upper 30 m of 11 California platforms, fish densities were 2.8 times higher surrounding beams spanning the inside of the jacket relative to the external jacket beams that were surveyed in this study (Meyer-Gutbrod et al. 2019*a*). However, there is no data available to verify whether this trend of higher densities inside the jacket is consistent at other California platforms or at depths below 30 m where only submersible and ROV surveys are available.

The biological metrics estimated in the total jacket volume method provide an estimate of the maximum fish assemblage size at each platform site. Fish densities are often highest in close proximity to structure (Meyer-Gutbrod et al. 2019*a*), which indicates that using densities observed over the horizontal beams to characterize some of the more open areas inside of the jacket between major beams may lead to an overestimation with the total jacket method. However, none of the three scaling methods account for the halo of fish habitat found outside of, but in close proximity to, the platform jacket. Fish densities just outside the platform jacket have been

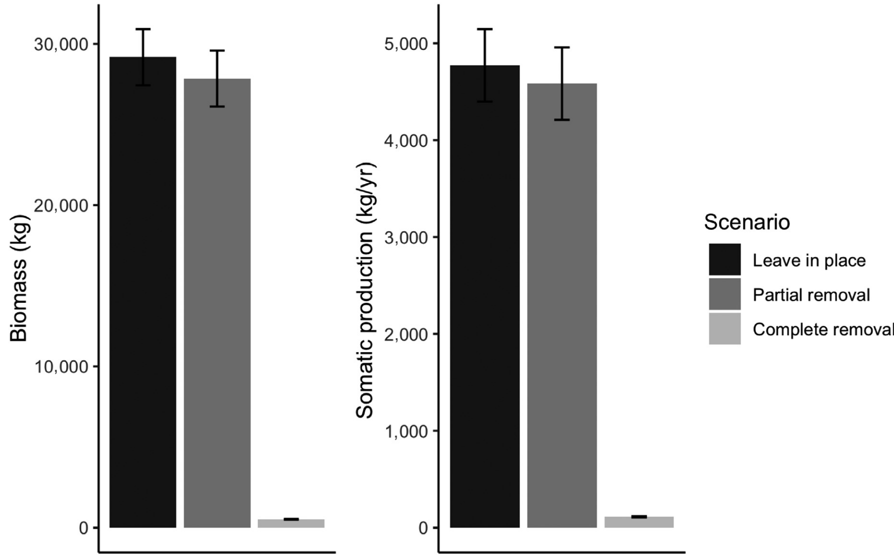

FIG. 6. Summed total of the mean (A) fish biomass (kg) and (B) annual somatic production (kg/yr) at all 24 platforms included in this study projected under three potential decommissioning scenarios: leave in place, partial removal at 26 m depth, and complete removal. The leave-in-place and partial-removal scenario estimates are based on the beam-slices scaling method. Error bars represent the standard error propagated from summing the contributions from each platform site.

noted to be considerably higher than in open pelagic environments (Soldal et al. 2002, Scott et al. 2015, Reynolds et al. 2018). Therefore, the total jacket volume method may not necessarily overestimate fish abundance. Future high-resolution survey efforts could be implemented to increase the precision in the total fish community size estimates, which probably fall somewhere between the beam slices and total jacket volume approaches.

Removal of the shallowest 26 m of a platform may impact communities in the remaining artificial reef by reducing shell mound formation or recruitment of shallow larvae and juveniles. Since most mussel growth on the platform occurs above 26 m, removal of the shallowest portion of the jacket will curtail the continued formation of the shell mound at the rig base (Page et al. 2005, Meyer-Gutbrod et al. 2019*b*). Persistence of the current shell mound and changes to its biota will depend on local currents and sedimentation rates as well as the reduction in mussel production (Bomkamp et al. 2004, Claisse et al. 2015). Enhancement of the artificial reef by depositing the structure removed from the upper 26 m of the water column alongside the rig base or adding other material such as rock (Holbrook et al. 2000) would create new complex habitat and increase the size of the benthic fish community. Young-of-the-year rockfishes are most abundant on platform regions deeper than 26 m, suggesting that partial removal will not adversely affect larval settlement onto the structure (Nishimoto and Love 2011). Comparisons between young-of-the-year assemblages on platforms, submerged shipwrecks and natural reefs indicated that the extension of structure to the sea surface on platforms did not impact rockfish recruitment to deeper habitats below 26 m (Love et al. 2012). The dominant species lost in the partial-removal scenario, *Chromis punctipinnis* (Fig. 4), is regionally abundant and not commercially valuable; however, it may function as an important prey group for higher trophic levels. Although there is significant species overlap between the platform midwaters, base, and shell mound (Fig. 5), diversity is lowest in the platform midwaters (Appendix S1: Fig. S2, Table S3), indicating that the partial-removal scenario will not result in much decrease in overall diversity at the site.

Survey coverage was not sufficient to provide a robust estimate of fish biomass and somatic production at all southern California platforms. Although limited data on platforms Esther and Eva have been reported elsewhere (Martin and Lowe 2010), fish surveys have never been conducted on Platform Emmy. Of the platforms included in this study, Harmony, Heritage, and Houchin have only been surveyed once. The estimates of decommissioning impacts at these sites are not as reliable as the estimates for sites with higher survey effort because there is considerable temporal variability in fish assemblage size and composition (Claisse et al. 2014, Love et al. 2019, Meyer-Gutbrod et al. 2019*b*). Additional, more frequent, survey effort would be beneficial to adequately inform the decommissioning process for these and other platforms.

Differences between fish behavior, such as attraction or avoidance, associated with the presence of a SCUBA diver, manned submersible, ROV, and bottom trawl may vary. These small, but potentially biased discrepancies between survey styles could not be accounted for in this study since surveys were never conducted simultaneously from two or more different platforms. There is a growing body of literature examining bias due to observation platform, and further work in this field should improve accuracy in visual and extractive methods in fish density estimation (Stanley and Wilson 1995, Weinberg et al. 2002, Trenkel et al. 2004, Stoner et al. 2008). Differences in trawl gear and methodologies between the SCCWRP and WCGBT surveys used in this study may also lead to biases in soft-bottom fish community size and species composition. Variation in cod end mesh size, footrope length, trawl speed, and duration can contribute to these differences (Stergiou et al. 1997, Somerton et al. 2002, Weinberg et al. 2002). Diversity indices are higher in WCGBT surveys compared to SCCWRP surveys (Appendix S1: Fig. S2, Table S3), although species composition is similar (Fig. 5), indicating that the smaller SCCWRP trawls may miss some species.

Fish density and community composition are also subject to interannual variability, which could not be fully captured in this study due to differences in survey timing and frequency between sites and habitat types. Studies of the subset of platforms that are surveyed regularly have suggested that much of the observed interannual variability at these sites is driven by rockfish recruitment dynamics and the random nature of sampling large, mobile schools (Love et al. 2006, 2019, Meyer-Gutbrod et al. 2019). Fish community composition and size may also exhibit some seasonal variability. Although the surveys included in this study were primarily conducted in the summer and fall, many of the rockfish species observed on the platforms are resident throughout the year, reducing the impact of seasonal variability (Lowe et al. 2009, Martin and Lowe 2010). Rockfishes have long reproductive seasons and exhibit significant seasonal variability within and among the different species (Echeverria 1987), indicating that survey timing may not dramatically impact juvenile counts. However, additional surveys conducted in winter and spring would be useful to determine the impact of sampling season on the results of this study.

Although fish biomass and somatic production estimates for each platform provide a measure of the main impacts of decommissioning at each site, a holistic analysis could include several additional ecological metrics. Comparison of the invertebrate community above and below 26 m and on the soft bottom may be possible using video recordings of the submersible surveys paired with trawl surveys. Fish collection efforts would be useful for examining the differences in growth rates and egg production on platforms relative to natural reefs. Larger scale comparisons of the value of platform habitat for commercially fished or at risk species such as *Sebastes levis* or *Sebastes paucispinis* with the effect of platforms on soft-bottom habitat for commercially fished species such as *Citharichthys stigmaeus* would be valuable. Oceanographic connectivity analyses may reveal the significance of these artificial reefs to the regional distribution and population genetic structure of fish species.

Previous studies of fish assemblages on California platforms have focused on the habitat and biological community that would be lost when the platform jacket, conductors, and shell mound are removed during the decommissioning process (Love et al. 2003, Claisse et al. 2014, Pondella et al. 2015). This study extends these efforts by considering the habitat and biological communities that would be gained under this scenario as the seafloor reverts back to productive soft-bottom habitat. The assumption that this habitat will be devoid of fish following complete removal of the structure and shell mound is problematic, and leads to biased predictions of fish loss under alternative decommissioning scenarios. This study examines the transformation, rather than loss, of habitat to present more accurate predictions of fish community size and composition following a range of decommissioning scenarios.

Habitat transformation following platform removal results in the exchange of reef habitat for trawlable soft-bottom habitat. Over 500 offshore platforms in the North Sea (Fowler et al. 2018) and nearly 2,000 installations in the Gulf of Mexico (Kaiser et al. 2019) limit trawlable habitat in ocean basins that are subject to intense fishing pressure. Offshore installations create no-trawl zones, which act as de facto marine reserves, possibly increasing productivity similar to a marine protected area (Schroeder and Love 2002, Love et al. 2003). However, no-trawl zones increase competition for space, increase costs for traveling to trawlable areas, and may displace fishing activities into habitats that are more vulnerable to disturbance (Kaiser et al. 2002, Bloomfield et al. 2012).

Disagreement between stakeholders on the optimal use of decommissioned platform habitats as either artificial reef or the preceding soft-bottom habitat extend to preferences in which species will inhabit these spaces. This study found no evident overlap in community structure between the soft-bottom habitat and the platform habitats and it is difficult to compare the value of platform habitat for commercially fished or at risk species such as *Sebastes levis* or *Sebastes paucispinis* with the value of commercially fished soft-bottom species such as *Citharichthys stigmaeus.* Since species composition varies by depth on both soft-bottom and artificial reef habitats (Bradburn et al. 2011, Love et al. 2019), the community transformation following structure removal may be examined in more detail at each site. Additionally, fish assemblages in the leave in place and partial-removal scenarios may differ from those presented in this analysis if fishing near these sites increases after decommissioning. Maximizing fish biomass and production on infrastructure converted to artificial reefs, therefore, will depend on future regulation of fishing at these sites. In the complete-removal scenario, the site of the platform footprint will likely become available for fishing, and therefore the species composition and density found in the trawl surveys used in this study are an accurate prediction of the future fish community. Deciding the ultimate fate of these structures and their management with respect to fish habitat will require a careful assessment of the complex costs and benefits associated with each alternative.

There are a host of additional factors besides fish communities that must be weighed when considering decommissioning alternatives. For a complete environmental impact analysis, studies must be conducted to assess the effects of pollution related to the dismantling, transport and recycling of structural elements, navigational considerations, resuspension of contaminants trapped under the shell mound, fishing impacts and the effects of explosives on surrounding marine life (Schroeder and Love 2004, Fowler et al. 2014). Beyond environmental impacts, decommissioning strategies will also include considerations for safety, economics, politics and aesthetics. These issues are multi-faceted and decisions should be made following input from a diverse range of stakeholders. However, the fish community forecasts presented here demonstrate that complete removal of California oil platforms will result in a net loss of local and regional fish biomass and production. These results constitute a critical component of the net environmental benefit analysis of California oil and gas platform decommissioning alternatives.

Conclusions

This study forecasts the biomass and somatic production of the fish communities associated with each of 24 oil and gas platforms in the Southern California Bight under three potential decommissioning scenarios to inform net environmental benefit comparisons of decommissioning alternatives (California Marine Resources Legacy Act 2010, Pérez 2010). The annual somatic production that would be lost if all 24 platforms are completely removed is equal to 13% of the annual Santa Barbara Harbor commercial fishing landings. However, the majority of the fish biomass and annual somatic production at each site will be preserved if the deep portion of the structure is converted to an artificial reef. The fish assemblage forecasts estimated here for most Pacific Outer Continental Shelf platforms can contribute to the development of a decommissioning strategy that minimizes the ecological impacts of decommissioning and maximizes benefit to the marine environment.

The substantial loss in fish biomass and somatic production predicted to occur at California offshore platform sites in the scenario where all structure is removed has meaningful implications for platform decommissioning decision-making worldwide. The ecosystems beneath most California platforms have been exceptionally well surveyed compared to regions that have much higher numbers of offshore platforms, such as the North Sea and the Gulf of Mexico. With thousands of platforms globally eventually facing decommissioning (Parente et al. 2006, IHS Markit 2016), survey efforts in each region should be expanded to determine whether platforms in other ocean basins have similar ecological effects. The Gulf of Mexico has the most active rigs to reefs program, where artificial reef conversion has been implemented for more than 500 of the nearly 5,000 structures that have been decommissioned (Rigs to Reefs 2017, Bull and Love 2019, Kaiser et al. 2019). Although research documenting biotic assemblages on reefed installations in the Gulf of Mexico (e.g., Ajemian et al. 2015) is sparse, additional survey effort at these sites combined with close monitoring of the ongoing decommissioning process in California would provide critical information for the rigs-to-reef discussions that are active in regions such as the North Sea, Australia, and the Gulf of Thailand.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.2185/full

Data Availability

The authors declare that all data supporting the findings of this study can be found in the following online repositories. The fish surveys conducted on platform-associated habitats are available on the two EDI Data Portal at https://doi.org/10.6073/pasta/2dc1e7a1ce14e0f3f070076fc4a85e43; https://doi.org/10.6073/pasta/af1f2c8a402c84b0b6fc17b73a950988. The NOAA West Coast Groundfish Bottom Trawl data are available from the NOAA Northwest Fisheries Science Center at https://www.webapps.nwfsc.noaa.gov/apex/parrdata/inventory/datasets/dataset/131. The Southern California Coastal Research Project trawl data are available at http://sccwrp.org/Data/SearchAndMapData/DataCatalog.aspx.