Fish densities associated with structural elements of oil and gas platforms in southern California

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ABSTRACT.—There are thousands of offshore oil and gas platforms worldwide that will eventually become obsolete, and one popular decommissioning alternative is the "rigs to reefs" conversion that designates all or a portion of the underwater infrastructure as an artificial reef, thereby reducing the burden of infrastructure removal. The unique architecture of each platform may influence the size and structure of the associated fish assemblage if different structural elements form distinct habitats for fishes. Using scuba survey data from 11 southern California platforms from 1995 to 2000, we examined fish assemblages associated with structural elements of the structure, including the major horizontal crossbeams outside of the jacket, vertical jacket legs, and horizontal crossbeams that span the jacket interior. Patterns of habitat association were examined among three depth zones: shallow (<16.8 m), midwater (16.8–26 m), and deep (>26 m); and between two life stages: young-of-the-year and non-young-of-the-year. Fish densities tended to be greatest along horizontal beams spanning the jacket interior, relative to either horizontal or vertical beams along the jacket exterior, indicating that the position of the habitat within the overall structure is an important characteristic affecting fish habitat use. Fish densities were also higher in transects centered directly over a vertical or horizontal beam relative to transects that did not contain a structural element. These results contribute to the understanding of fish habitat use on existing artificial reefs, and can inform platform decommissioning decisions as well as the design of new offshore structures intended to increase fish production.

More than 7500 offshore oil and gas platforms worldwide (Parente et al. 2006) function as habitat for productive and diverse fish assemblages, including in the North Sea (Soldal et al. 2002), the Gulf of Mexico (Scarborough Bull and Kendall

1994, Stanley and Wilson 1997, Gallaway et al. 2009), the Gulf of Guinea (Friedlander et al. 2014), the Persian Gulf (Torquato et al. 2017), the Adriatic Sea (Fabi et al. 2004), off Australia (Neira 2005), and off California (Love et al. 2003, Claisse et al. 2014). Due to the ecological and economic value of these marine communities, as well as the high cost of platform decommissioning (Smith and Speck 2015, IHS Markit 2016), retention of a portion of the underwater structure for use as an artificial reef, sometimes called "rigs to reefs," may be considered as an alternative to full removal (Macreadie et al. 2011, Fowler et al. 2014, Bull and Love 2019). The best environmental outcomes of decommissioning may come from considering each platform on a case-by-case basis (Schroeder and Love 2004, Fowler et al. 2018). When assessing each platform's value as a fisheries resource, it is useful to understand how fish associate with these structures.

Artificial reefs may increase the biomass and production of fish by increasing suitable habitat area. Many reef and demersal fishes associate with structure, which is often assumed to reduce risk of predation (Robertson and Sheldon 1979, Hixon and Beets 1989, Pickering and Whitmarsh 1997, Love and York 2006). Structure availability is considered especially important for small fishes, particularly juveniles and dwarf species (Anderson et al. 1989, Rabaoui et al. 2015, McLean et al. 2017). Therefore, fish densities are typically high in close proximity to artificial reefs, and rapidly decrease with distance away from the structure (Soldal et al. 2002, Wilson et al. 2003, Scott et al. 2015, Bond et al. 2018, Reynolds et al. 2018).

Artificial reef design and location have a significant impact on the structure of the biotic community that develops there. The shape and orientation of the structure can influence species composition and catch rates (Lee and Kang 1994, Kim et al. 1994, Bond et al. 2018, Reynolds et al. 2018). Structural complexity also significantly impacts fish diversity and abundance (Charbonnel et al. 2002, Sherman et al. 2002, Bond et al. 2018, McLean et al. 2018). Total fish biomass on artificial reefs scales up with the size of the underwater structure (Bombace et al. 1994, Bohnsack et al. 1994). The vertical extent of a structure into the water column transforms pelagic to high-rise reef habitat (Klima and Wickham 1971, Jessee et al. 1985, Anderson et al. 1989, Macreadie et al. 2011, Claisse et al. 2014, Pradella et al. 2014). Artificial reefs located far from natural reefs may be more likely to contribute to total regional fish production, rather than simply hosting temporary visitors from nearby habitats (Rountree 1989, Bohnsack 1989).

In southern California, 27 offshore oil and gas platforms in bottom depths ranging from 9 to 363 m provide artificial reef habitat for diverse and productive fish communities (Love et al. 2003, Martin and Lowe 2010, Claisse et al. 2014, Pondella et al. 2015). The underwater structural elements of each platform are dominated by a steel frame, or jacket, supporting the topside structure, and large conductor pipes that support the oil well. Many of the platforms are located in the productive upwelling system of the Santa Barbara Channel (Brzezinski and Washburn 2011) and are anchored into soft, muddy substrate, at depths where natural rocky reefs are sparse (Love et al. 2003). Because the structures extend through the entire photic zone, they often host highly productive communities of suspension feeders (Page 1986, Page and Hubbard 1987, Reeves et al. 2018) and provide hard structure for fish throughout the water column (Allen et al. 1987, Claisse et al. 2014, 2015, Meyer-Gutbrod et al. 2019). Due to their remote location, strong currents and site-specific regulations,

fishing is difficult at many of these platform sites, and the artificial reefs function as de facto marine reserves (Schroeder and Love 2004).

A critical decision in the platform decommissioning process is whether to remove the entire structure, leave it in place, or remove a portion of the structure (Schroeder and Love 2004). One of the challenges of comparing the environmental costs and benefits of these decisions is assessing the artificial reef function of the individual existing platforms. Such assessments should consider the value of particular structural elements of these artificial reefs as potentially distinct habitats for fish. Using scuba surveys of fish species composition and abundance on 11 southern California platforms within the time period 1995–2000, we evaluated fish association with several platform structural elements. We quantified fish associations among these potentially distinct habitats based on the presence of beams, beam orientation, and beam position within the structure. Finally, we assessed whether patterns in fish habitat use were dependent on species, life stage, or depth zone. The goal of this analysis was to determine how different structural elements within platforms function as fish habitat. Ultimately, the results will improve platform-wide estimates of fish production and diversity that are used to inform platform decommissioning decisions. In addition, a better understanding of fish associations with distinct structural features of an artificial reef may contribute to the design of purpose-built artificial reefs and future offshore installations, such as new oil and gas platforms or wind turbines, for optimal fish habitat.

Methods

Platform Surveys.—Fish surveys were performed by scuba divers on 11 active platform sites between 1995 and 2000 (Fig. 1, Table 1). Surveys were conducted during daylight hours, and most were conducted from midsummer to early fall (July–October; Fig. 2). Surveys were conducted along belt transects 2 m wide and 2 m high. Divers recorded the species and total length (to the nearest centimeter) of each fish encountered in the transect volume (Fig. 3). Fish behavior may be affected by the presence of divers (Stanley and Wilson 1995, Dickens et al. 2011), but we were unable to account for this possibility.

Pairs of divers conducted the surveys, each surveying a 2 m belt transect while descending a different vertical jacket leg (VT) until reaching the deepest beam present above 37 m (Fig. 4). Each diver then ran three surveys along the full length of one exterior horizontal crossbeam on the jacket: a 2 m belt transect centered on the beam (HZM), a belt transect parallel to the beam in the jacket interior spanning a distance from 1 to 3 m away from the center of the beam (HZI), and another 2 m belt transect outside of the jacket, parallel to the beam, spanning a distance from 1 to 3 m away from the center of the beam (HZO; Fig. 4 inset). The diver surveyed a portion of the adjoining perpendicular external crossbeams (typically about one-third of the total beam length) until they reached a horizontal crossbeam spanning the jacket interior (HZU). These 2 m belt transects were centered on the external beams perpendicular to HZM and were included in the HZM transect because the structural elements were identical (Fig. 4 inset). Next, the full length of the horizontal crossbeam spanning the jacket interior (HZU) was surveyed as a 2 m belt transect centered on the beam. Finally, the diver ascended to the next major horizontal crossbeam or depth level, while conducting a 2 m belt transect centered on another leg (VT; Fig. 4 inset).
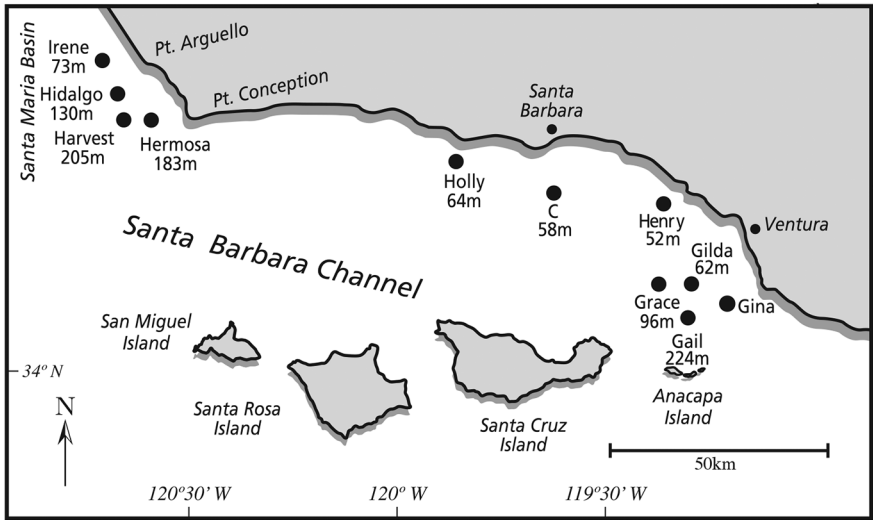
Figure 1. Map of the 11 offshore platforms in southern California where scuba divers conducted fish surveys from 1995 to 2000.

Following this pattern, the diver conducted fish surveys in a spiral pattern up to the surface, surveying fishes at each beam level and on the vertical legs. The other diver in the buddy pair would mirror the first diver's survey pattern using the remaining two vertical jacket legs as guides. Transect lengths varied depending on the size and shape of the platform jacket, as jacket width at the surface can range from 11 to 62 m depending on the site (Allen et al. 1987).

Up to three depth levels were completed at each platform (Fig. 4). The depth of each vertical transect was defined by the depth of the horizontal transects surveyed directly below it. Each of the depth levels typically contained a major exterior horizontal crossbeam on the jacket. At platform sites where there were fewer than three exterior horizontal crossbeams above a depth of 37 m, divers would still

Table 1. Characteristics of the southern California platforms included in this study. Platforms are listed in alphabetical order. Footprint is the area of the platform base at the seafloor, calculated as the product of the length and width of the jacket at the base.

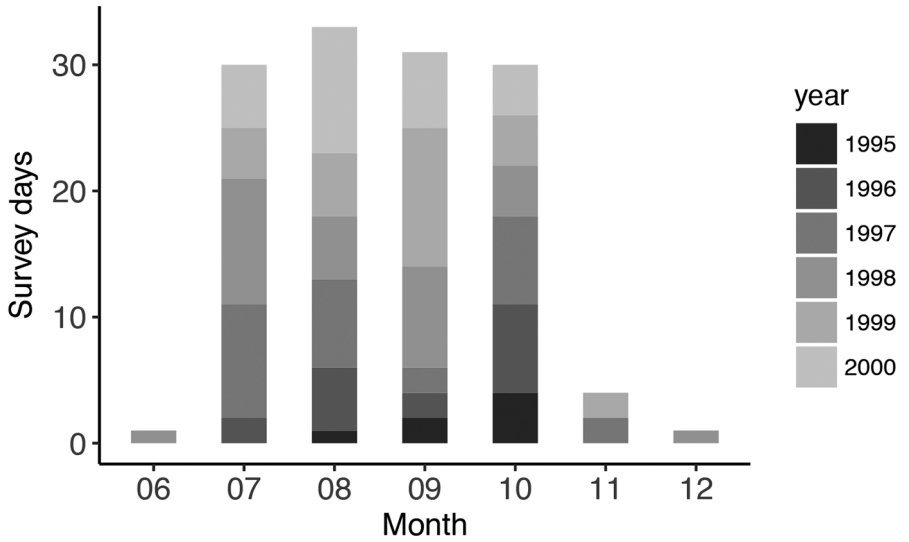| Platform	Year installed	Sea floor depth (m)	Jurisdiction	Footprint (m²)	Transects surveyed	Sampling days	Total fish count	Fish density (per 100 m²)
C	1977	58	Federal	1,930	28	1	502	27.88
Gail	1987	224	Federal	5,327	325	13	10,605	54.90
Gilda	1981	62	Federal	2,342	405	17	16,608	68.62
Gina	1980	29	Federal	561	216	15	4,878	63.27
Grace	1979	96	Federal	3,090	360	13	12,334	52.96
Harvest	1985	205	Federal	5,859	317	12	13,861	50.12
Henry	1979	52	Federal	1,505	28	1	391	29.16
Hermosa	1985	183	Federal	5,142	321	12	5,485	23.74
Hidalgo	1986	130	Federal	4,154	352	13	8,269	27.12
Holly	1966	64	State	1,728	446	17	27,841	112.09
Irene	1985	73	Federal	2,633	390	16	24,715	100.14

Figure 2. Survey effort bar chart showing the number of sampling days when surveys were conducted in each month for each year.

complete the same rectangular survey between jacket legs where there was no horizontal beam present; these transects were not included in the analysis comparing fish densities between the five distinct transect types, but were used in a comparison of fish community structure between depth levels with and without a crossbeam present. Since crossbeam depths varied between platforms, transects were grouped
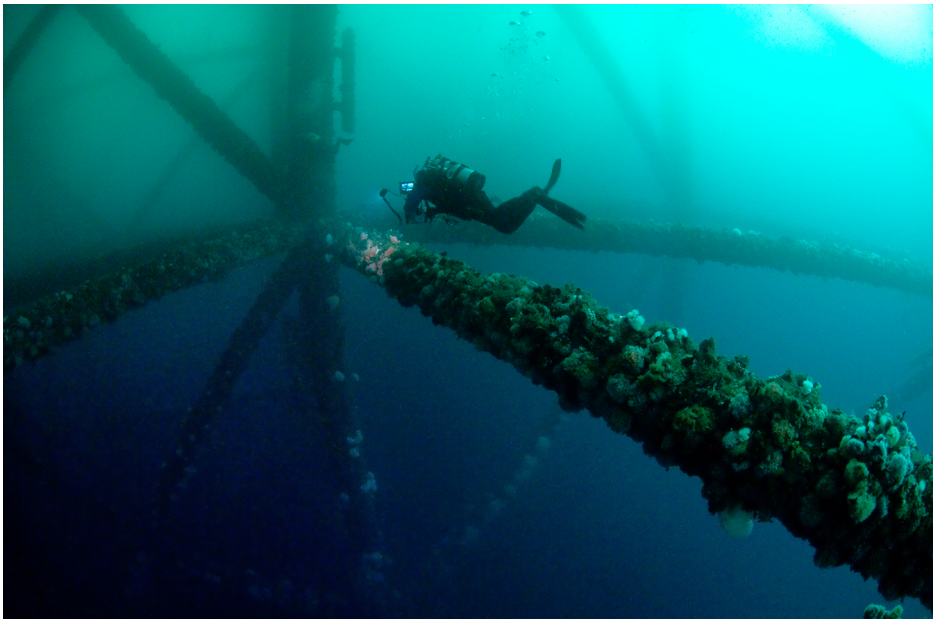

Figure 3. Scuba diver conducting transect survey over a horizontal crossbeam covered with invertebrates on Platform Gilda. Photo credit: S Gietler.
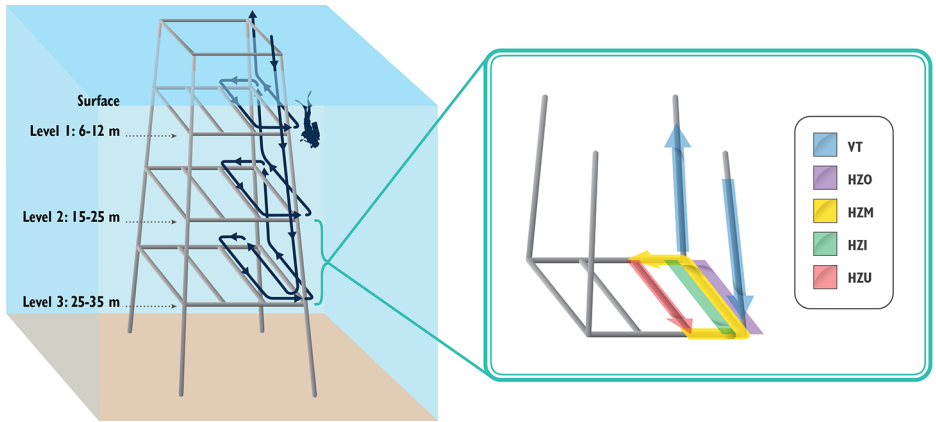
Figure 4. Scuba dive pattern surveying around three horizontal beam levels and two adjacent vertical jacket legs. A second diver (not shown) would complete a mirrored survey pattern surveying along the three horizontal beam levels and remaining two vertical legs on the left side of the platform. Modified from Love et al. 2003 (fig. 1.7). Inset shows schematic of the independent transects surveyed by the diver. The three adjacent 2 m transects surveyed along the exterior horizontal beam (HZI, HZM, and HZO) are surveyed concurrently, effectively as one 6 m wide belt transect over the beam. The horizontal beam under the platform (HZU) and the vertical beams (VT) are surveyed as 2 m belt transects.

into three depth zones: shallow (<16.8 m), middle (16.8–26 m), and deep (>26 m), to compare depth-dependent variability in species composition between sites.

Statistical Analysis.—Fish counts were converted to densities by dividing the number of fish found on a particular transect by the area surveyed (transect length × 2 m). All densities are reported as number of fishes per 100 m^2 surveyed. Replicate surveys by the diver team of each structural element at a given platform, depth level and date were averaged. Pelagic fishes, such as Pacific sardine, *Sardinops sagax* (Jenyns, 1842), and Pacific jack mackerel, *Trachurus symmetricus* (Ayres, 1855), were removed from the analysis as they are transient and were assumed to have no strong association with any structural element. To determine the effect of life stage on fish habitat use, we used fish length to classify individual fish as young-of-the-year (YOY) or older than YOY (non-YOY) based on life stage length cut-off data from Love et al. (2002, 2012), and Love (2011).

We examined the effect of structural element on fish density for all surveys conducted at depth levels where horizontal beams were present. We first examined the overall effects of structural element on fish density, and then tested the effects of structural element on the density of each life stage broken into the three distinct depth zones. Finally, we examined the effects of structural element on the density of the six most common species found on the platforms. Fish density data did not meet assumptions of normality; therefore, we used the Kruskal-Wallis test by ranks followed by the Dunn post hoc test (α = 0.05) for pairwise comparison.

To examine observed differences in the fish community structure, we constructed separate Bray-Curtis dissimilarity matrices for species-specific non-YOY fish densities and YOY densities. Permutational analysis of variance (adonis in R vegan package; R Core Team 2017, Oksanen et al. 2018) was performed on each dissimilarity matrix using 999 permutations to simultaneously test the effects of survey year,

structural element, the presence of a horizontal beam at the surveyed depth level, depth category, and platform. The five-factor permutational analysis of variance was run separately for the YOY fish community and again for the non-YOY community. Post hoc multilevel pairwise comparisons were conducted for each significant factor in the permutational analysis of variance analyses (pairwiseAdonis package in R; R Core Team 2017, Martinez Arbizu 2019). *P*-values for multiple comparisons were adjusted using the Bonferroni correction (Bland and Altman 1995). Finally, we conducted a similarity percentage analysis to determine the contribution of each species to the average overall Bray-Curtis dissimilarity matrix of the YOY and non-YOY communities between structural elements (simper in R vegan package; R Core Team 2017, Oksanen et al. 2018).

Results

A total of 3188 transects across 11 platform sites were included in this study. Divers encountered 125,489 fishes representing 38 taxa or taxonomic groups (Online Table S1). Observations were dominated by the rockfish genus *Sebastes* (57%), especially by *Sebastes entomelas* (*see* Online Table S1 for species authorities) (widow rockfish, 30%), *Sebastes mystinus* (blue rockfish, 10%), *Sebastes hopkinsi* (squarespot rockfish, 8%), and *Sebastes paucispinis* (bocaccio, 6%). *Chromis punctipinnis* (blacksmith) was the second most common species observed (29%) (Table S1). The majority of fish included in this study were YOY (72%).

Differences in overall fish density between the five platform structural elements were examined, and fish densities on the interior horizontal beam that crosses underneath the platform (HZU) were significantly higher than in the four other habitat types surveyed (Fig. 5). In the set of three transects surveyed along the exterior jacket horizontal crossbeam (i.e., HZO, HZM, and HZI), densities were highest in the 2 m swath centered on the crossbeam (HZM), followed by the 2 m swath running just inside of the jacket (HZI). Fish densities were lowest on HZO, which was the only
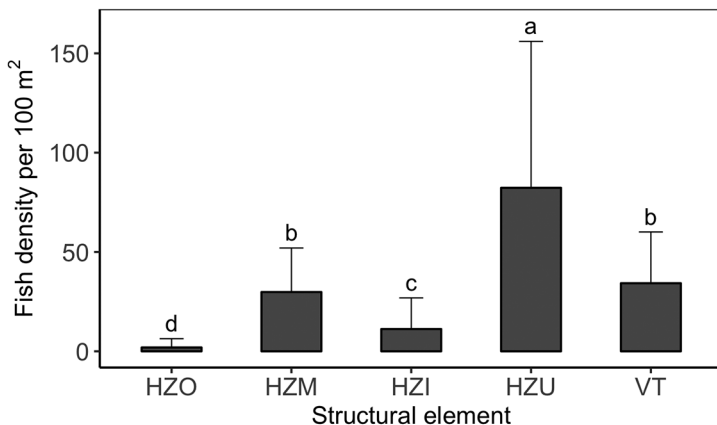

Figure 5. Median fish densities (count per 100 m^2) and interquartile range on transects in five platform habitats: outside the external horizontal beam (HZO), straddling the external horizontal beam (HZM), inside the external horizontal beam (HZI), straddling an interior horizontal beam underneath the platform (HZU) and a vertical transect along a jacket leg (VT). Letters above interquartile range bars indicate structural elements that are not significantly different following Dunn's test of multiple comparisons (α = 0.05).
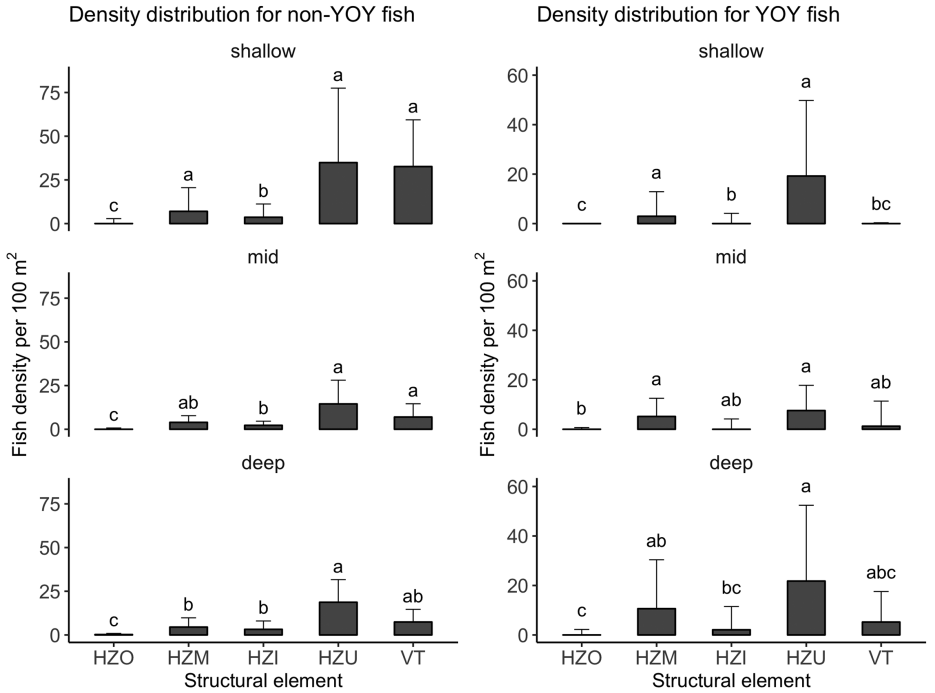
Figure 6. Median fish densities (count per 100 m²) and interquartile range on transects of non-young-of-the-year (non-YOY; left) and young-of-the-year (YOY; right) among five platform habitats: outside the external horizontal beam (HZO), straddling the external horizontal beam (HZM), inside the external horizontal beam (HZI), straddling an interior horizontal beam underneath the platform (HZU) and a vertical transect along a jacket leg (VT). Densities are separated into three depth strata: shallow (<16.8 m), middle (16.8–26 m), and deep (>26 m). Letters above interquartile range bars indicate structural elements that are not significantly different within a given life stage and depth strata following Dunn's test of multiple comparisons (α = 0.05).

transect in the study located completely outside of the platform jacket (Fig. 5). Fish densities on the exterior vertical jacket legs (VT) were similar to those found on the exterior horizontal beams (HZM; Fig. 5). All three transect types that were centered on a beam (HZM, HZU, and VT) had significantly higher fish densities than the two transect types that did not include a structural element (HZI and HZO; Fig. 5).

Investigations of the factors that drive fish associations with structural elements revealed that patterns in habitat association were similar across both life stages and the three depth zones (Fig. 6). Fish densities were higher on the horizontal crossbeam under the platform (HZU) compared to all other habitat types for both YOY and non-YOY in all three depth zones (Fig. 6). Densities under the platform (HZU) were significantly higher than densities outside of the jacket (HZO) for all life stages and depth zones (Fig. 6). The lowest densities for all life stages and depth zones were found along the transects that did not contain a structural beam (HZO and HZI; Fig. 6).

The six most common species found in the platform surveys accounted for 85% of all fish observed (Fig. 7, Table S1). *Sebastes entomelas,* the most commonly observed species on the platforms (30%), and *S. hopkinsi* (8%) exhibited minimal differences in habitat association. Three of the most common species, *C. punctipinnis* (29%), *S. mystinus* (10%), and *S. paucispinis* (6%), exhibited habitat associations similar to
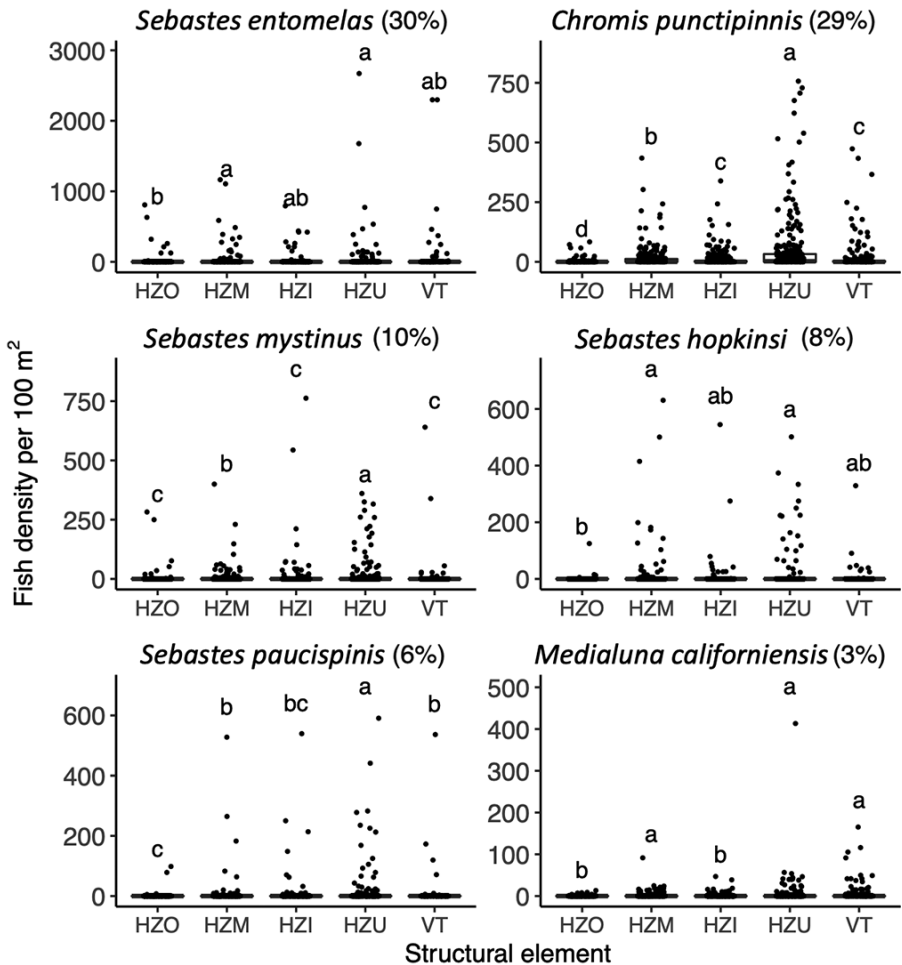
Figure 7. Fish density (count per 100 m²) box plots overlaid with density observations of the six most common fish species found on the platforms. Young of the year and non-YOY were combined for each species. Observed densities are shown among five platform habitats: outside the external horizontal beam (HZO), straddling the external horizontal beam (HZM), inside the external horizontal beam (HZI), straddling an interior horizontal beam underneath the platform (HZU) and a vertical transect along a jacket leg (VT). Plot labels contain species name and percent contribution to all fish observations collected. Letters above maximum value outliers indicate structural elements that are not significantly different within a species following Dunn's test of multiple comparisons (α = 0.05).

the dominant pattern across all species, with more high-density observations occurring along the transect under the platform (HZU) relative to the other habitats (Fig. 7). The densities under the platform (HZU) were significantly higher compared to those outside of the platform (HZO) for all six species. *Medialuna californiensis* (halfmoon, 3%) exhibited a simple pattern of significantly higher densities on transects centered on beams (HZM, HZU, and VT) than transects that are not centered on beams (HZO and HZI; Fig. 7).

To examine drivers of fish community structure, we conducted permutational analysis of variance using survey year, structural element, depth zone, the presence

Table 2. Results of two permutational analysis of variance tests examining the effects of survey year, structural element, presence of horizontal beams at that depth level, depth zone and platform on non-young-of-the-year (non-YOY) fish densities and YOY densities. *P*-values below α = 0.05 are shown in bold.

Variable	df	*F*-value	R^2	*P*-value
Non-YOY				
Year	5	8.39	0.057	**0.001**
Structural element	4	4.63	0.025	**0.001**
Horizontal present	1	10.32	0.014	**0.001**
Depth zone	2	20.01	0.055	**0.001**
Platform	10	12.62	0.173	**0.001**
YOY				
Year	5	9.23	0.103	**0.001**
Structural element	4	2.18	0.019	**0.001**
Horizontal present	1	1.18	0.003	0.278
Depth zone	2	10.60	0.047	**0.001**
Platform	10	3.21	0.071	**0.001**

of a horizontal beam at the surveyed depth level, and platform to explain patterns of YOY and non-YOY densities across species (Table 2). All variables had a significant effect on community structure, with the exception of the presence of a horizontal beam for the YOY communities (Table 2).

The results of the similarity percentage analysis indicated that >70% of the variation in the YOY community structure between structural elements was driven by *C. punctipinnis*, *S. entomelas*, *Sebastes atrovirens* (kelp rockfish), *S. paucispinis*, and *S. mystinus.* Greater than 70% of the variation in the non-YOY community structure between structural elements was driven by *C. punctipinnis*, *M. californiensis*, *Paralabrax clathratus* (kelp bass), and *Oxylebius pictus* (painted greenling).

Pairwise comparison among environmental factors in the YOY and non-YOY community analyses revealed that variation in structural element as well as presence of horizontal beams at a depth level had more of an impact on the non-YOY compared to YOY community structure (Table 3). Survey year affected community structure of both YOY and non-YOY life stages, with 1999 standing out as a significant factor relative to every other year surveyed (Table 3). Community structure also varied among all three depth zones for both life stages (Table 3). None of the pairwise comparisons between platform sites were significant in either the YOY or non-YOY analysis, and were therefore not included in Table 3. While the individual R^2 values of each pairwise comparison within the community analysis are low (Table 3), the overall amount of variance explained by the set of variables included in this study is reasonable given the complexity of species composition differences between habitats (Table 2). These results indicate that inclusion of fine-scale habitat variables would be valuable in broader models that are prevalent in the literature examining the effects of fishery structure, physical oceanography, and climate on fish community composition on natural or artificial reefs.

Table 3. Results of pairwise multiple comparisons tests from the non-young-of-the-year (non-YOY) density permutational analysis of variance and the YOY density permutational analysis of variance. These tests examine differences in community structure between four factors: structural element, year, presence of a horizontal beam and depth zone. Pairwise comparisons between platform sites were not significant and therefore not included in the table. P-values below $\alpha = 0.05$ are shown in bold.

Pairs	Non-YOY			YOY		
	F-value	R^2	Adjusted P-value	F-value	R^2	Adjusted P-value
Structural element						
HZI vs HZM	3.14	0.01	**0.02**	3.29	0.01	**0.01**
HZI vs HZO	0.92	0.01	1.00	0.89	0.01	1.00
HZI vs HZU	4.98	0.02	**0.01**	1.39	0.01	1.00
HZI vs VT	4.17	0.02	**0.01**	1.99	0.01	0.23
HZM vs HZO	1.89	0.01	0.55	1.22	0.01	1.00
HZM vs HZU	4.47	0.02	**0.01**	2.18	0.02	0.12
HZM vs VT	1.56	0.01	1.00	2.29	0.01	0.12
HZO vs HZU	5.28	0.03	**0.01**	0.98	0.01	1.00
HZO vs VT	3.41	0.02	**0.03**	1.57	0.01	0.96
HZU vs VT	2.90	0.01	**0.03**	1.11	0.01	1.00
Year						
1995 vs 1996	2.51	0.02	0.11	2.12	0.03	0.23
1995 vs 1997	3.23	0.02	0.05	1.89	0.02	0.68
1995 vs 1998	8.00	0.05	**0.02**	3.57	0.03	0.06
1995 vs 1999	7.65	0.05	**0.02**	7.74	0.07	**0.02**
1995 vs 2000	5.93	0.05	**0.02**	2.47	0.05	0.05
1996 vs 1997	2.42	0.01	0.26	4.40	0.03	**0.03**
1996 vs 1998	3.06	0.02	0.05	4.59	0.03	**0.02**
1996 vs 1999	5.26	0.03	**0.02**	11.24	0.08	**0.02**
1996 vs 2000	2.38	0.01	0.30	1.40	0.02	1.00
1997 vs 1998	7.44	0.03	**0.02**	6.31	0.03	**0.02**
1997 vs 1999	14.35	0.07	**0.02**	18.32	0.11	**0.02**
1997 vs 2000	9.46	0.05	**0.02**	4.12	0.04	**0.03**
1998 vs 1999	10.10	0.05	**0.02**	25.70	0.13	**0.02**
1998 vs 2000	4.52	0.02	**0.02**	6.36	0.05	**0.02**
1999 vs 2000	4.04	0.02	**0.03**	6.91	0.06	**0.02**
Horizontal present						
No vs yes	8.59	0.02	**0.00**	1.12	0.00	0.32
Depth category						
Shallow vs mid	13.29	0.04	**0.03**	9.36	0.04	**0.00**
Shallow vs deep	30.49	0.07	**0.03**	21.29	0.07	**0.00**
Mid vs deep	2.79	0.01	**0.03**	2.55	0.01	**0.01**

Discussion

Fish density and community structure varied significantly among the different types of structural features surveyed. Fish densities were higher on transects centered on a structural element, regardless of its orientation, compared to transects centered 2 m away from the structure (Fig. 5). The highest fish densities observed in this study occurred in association with beams that span the jacket interior and were

surrounded by the entire platform structure. Densities on these interior crossbeams were 2.8 times higher than on transects surveyed along the jacket exterior. Thus, while this study indicates that fish prefer to be in close proximity to hard substrate, the presence and relative position of distant structural elements also plays an important role in fish habitat associations.

One possible explanation for this phenomenon is that reef-associated fish species are adapted to prefer environments with higher structural density or complexity. Most species encountered during platform surveys, including the six most common species observed in this study, are typically associated with structure, such as rocky reefs and kelp forests (Love 2011). Although direct evidence of the benefits of structure are difficult to obtain, natural structures, such as rocks, corals, and seagrass meadows, have been asserted to provide shelter from predators (Main 1987, Beukers and Jones 1997). In southern California, giant kelp, the dominant structure forming organism, is positively associated with high abundance and diversity of reef fishes (e.g., DeMartini and Roberts 1990, Miller et al. 2018), potentially because giant kelp provides a source of food and shelter from predation or currents (Jackson and Winant 1983, DeMartini and Roberts 1990, Holbrook et al. 1990). Several experiments indicate that artificial reefs may function similar to kelp forests as habitat for reef fishes (Behrents 1987, Reed et al. 2006). Fish species with behavioral traits that evolved in such habitats may seek the most sheltered area available on an oil platform, regardless of whether any actual benefit is incurred. Further research investigating changes in predation pressure between different platform habitats could elucidate the effects of this behavior on fitness.

Habitat association between the five transect types included in this study did not differ significantly between depth zone and life stage: densities were consistently highest along the crossbeam spanning the jacket interior (HZU) and lowest on the transects that were not centered on a structural element (HZO and HZI; Fig. 6). However, fish densities were not considerably different among depth zones for either YOY or non-YOY life stages (Fig. 6). Diver surveys on offshore platforms on the San Pedro Shelf of southern California, which are farther south than the sites included in the present study, found higher densities of small fish in the corresponding shallow and middle depth zones (Martin and Lowe 2010). This difference may be explained by the warmer temperatures on the San Pedro Shelf, which result in a different species composition. Although rockfish YOY generally recruit to a shallower depth than the depth range occupied by conspecific adults, deeper-dwelling species typically recruit to deeper depths than shallower-dwelling species (Love et al. 1991). The entire 0–37 m depth range that can be surveyed by divers is shallow relative to the full range of water column depths at the 11 platforms included in our study (Table 1). YOY occur in high densities throughout the first 100 m of the water column at southern California platforms and natural reefs (Love et al. 2003, 2019) and further study of species-specific recruitment patterns with depth and geographic zone is warranted.

Variation in fish habitat association may also be a function of the invertebrates and algae living in different depth zones and habitats. Structure-forming invertebrates on the platforms, such as mussels and anemones, augment the shelter available to small fish. The density of small benthic mobile invertebrates like amphipod crustaceans was associated with the condition of *Oxylebius pictus*, a planktivorous reef fish common on California platforms (Page et al. 2007). Surveys of southern California natural reefs suggest that the presence and density of benthic macroinvertebrates does

not have a significant influence on the density of the majority of fish species observed (Tissot et al. 2006). However, additional research using combined invertebrate and fish surveys on California platforms may provide insight on whether observed variation in fish densities associated with different structure types is driven by invertebrate presence and density.

Some affinity for structure was demonstrated across all six of the most common species surveyed, since densities were consistently lowest along the horizontal transect outside of the jacket exterior (HZO; Fig. 7). For two species, *C. punctipinnis* and *S. mystinus*, significantly higher densities were observed on transects containing horizontal beams (HZM and HZU) compared to vertical beams (VT; Fig. 7). This indicates that for some species, structure orientation may be an important characteristic of habitat suitability. Further work should be conducted to determine the scope of structural orientation preference across a broader range of species and to elucidate potential mechanisms, such as differential invertebrate settlement. This type of research may be critical for guiding the optimal design of purpose-built artificial reefs.

Since not every platform was surveyed during each year of our study, these data are not well suited for time series analysis. However, across the whole set of platforms studied, fish densities were significantly higher in 1999, and significant differences were not consistently detected among any of the other years (Table 3). This observation is most likely driven by a previously documented large recruitment class of a number of taxa in 1999. Annual submersible surveys on Platform Gail from 1999 to 2004 followed this high recruitment class, which shifted to a deeper section of the platform structure as they aged (Love and York 2006).

Many artificial reefs are small, such as breakwalls, sunken vessels, intentional placement of rocks, tires, or concrete blocks, and total fish biomass on these small reefs makes a limited contribution to regional fish production (Baine 2001). In contrast, large artificial reefs have the highest potential to mitigate effects of environmental impacts and high fishing pressure (Ambrose and Swarbrick 1989, DeMartini et al. 1989). For example, a large artificial reef installment increased the economic value of a Japanese octopus fishery (Polovina and Sakai 1989) and the complex of southern California offshore oil and gas platforms may be contributing to rebuilding the regional stock of overfished *S. paucispinis* (Love et al. 2006).

Given this potential, an estimation of the contribution of offshore platforms to fish production will be critical when comparing the net environmental benefit of decommissioning alternatives. These impending assessments call for accurate estimates of the diversity and abundance of marine organisms that utilize the artificial reef. Repeated surveys of the complete structure are a complex and expensive undertaking, and it may be more feasible to survey across the range of platform structural features and extrapolate these assessments to total abundances.

The results of the present study will help contextualize previous platform fish surveys conducted along a subset of the structural elements reviewed here. Fish density, biomass, and production estimates for southern California platforms have typically been derived from manned submersible and ROV surveys that exclusively target exterior jacket beams (e.g., Love et al. 2003, 2019, Claisse et al. 2014). Application of these data to characterize total platform fish production should be done cautiously. Given that fish densities were higher in transects containing beams, if densities surveyed along structural beams are applied to the entire volume of water contained in the platform jacket, total fish biomass associated with the artificial reef will likely be

overestimated. On the other hand, fish densities observed along interior jacket beams (HZU) can be higher than densities along the exterior jacket crossbeams (HZM), so applying exterior horizontal beam densities alone to the total underwater surface area may result in an underestimate of total biomass.

Even as offshore oil drilling operations begin to decline (Heun and de Wit 2012), offshore wind turbines as well as wave and tidal energy installations will create similar substantial underwater infrastructure (Breton and Moe 2009, Rourke et al. 2010). Enhancement of the structural complexity of such alternative energy installations and other offshore structures could be investigated as a means to increase fish productivity on these de facto artificial reefs (Langhamer 2012, Callaway et al. 2017). Variation in fish habitat use across a range of artificial reef characteristics will be a critical consideration in guiding the future design of offshore installations and potentially maximizing their environmental benefit.

Acknowledgments

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