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Ichthyofauna associated with a no longer standing decommissioned oil plataform in the Tropical Eastern Pacific (4°S, Peru)

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Seabed resources contribute to one-third of global oil extraction, leading to the development of offshore oil platforms that act as artificial ecosystems supporting diverse fish and invertebrate assemblages. However, ecological studies on ichthyofauna associated with oil and gas structures along the Peruvian continental shelf remain limited. This study used underwater video footage collected across a depth gradient (0–40 m) divided into five strata around the MX-1 oil platform, located off Los Órganos (4°S, Piura, Peru), during austral spring (October 2022), using open-circuit SCUBA. Temperature and salinity were recorded with a hand-held CTD. Over six dives, a total of 7,969 individual fish were recorded, comprising 27 species from 13 families, including eight species targeted by fisheries. Fish belonged to two biogeographic provinces: Peruvian (n = 3) and Panamic (n = 20), with four species from the transition zone. Vertical distribution pattern was observed: species richness was highest in the shallowest stratum (0–5 m; n = 19), while fish abundance peaked in deeper layers (30–40 m). Carnivorous and planktivorous fish predominated. MX-1 functioned as a fish-aggregating device (FAD) and a local hotspot of fish diversity. Its partial removal could result in habitat loss, affecting associated assemblages, artisanal fisheries, and recreational activities.

Keywords: Artificial reef, Fish assemblages, Scientific diving, Underwater census, Vertical distribution.

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Un tercio de la extracción global de petróleo proviene del lecho marino, lo que ha impulsado la instalación de plataformas que crean ecosistemas artificiales atrayendo peces e invertebrados. Sin embargo, hay pocos estudios ecológicos sobre ictiofauna en estructuras en la plataforma continental del Perú. En octubre de 2022, se realizaron registros en vídeo a lo largo de un gradiente de profundidad (0–40m) en cinco estratos en la plataforma petrolera MX-1, Los Órganos (4°S, Piura, Perú), usando equipo SCUBA y midiendo temperatura y salinidad con un CTD compacto. Durante seis inmersiones se registraron 7,969 peces de 27 especies de 13 familias, incluidas ocho de interés comercial. Las especies corresponden a las provincias biogeográficas Peruana (n = 3), Panámica (n = 20) y una zona de transición (n = 4). La mayor riqueza de especies (n = 19) se encontró entre los primeros 5 m, mientras que la abundancia fue mayor en estratos profundos (30–40 m). Los grupos tróficos dominantes fueron carnívoros y planctívoros. MX-1 representaba un hotspot de diversidad de peces a nivel local (FAD). Su remoción parcial significaría la pérdida del hábitat artificial inicialmente creado, y esto generará una reestructuración y redistribución de la ictiofauna asociada, potencialmente impactando negativamente la pesquería artesanal local y actividades recreacionales.

Palavras-chave: Arrecifes artificiales, Buceo científico, Censo subacuático, Distribución vertical, Ensamble de peces.

INTRODUCTION

Seabed resources account for one-third of global oil extraction, which has instigated the construction and deployment of up to 12,000 oil-and-gas platforms around the world's continental shelves (Pulsipher, Daniel, 2000; World Ocean Review, 2014; Ars, Rios, 2017) where about 95% are fixed-type jacket platforms (Fu, 2018). These oil rigs extend along the entire water column from the surface to the seabed, conforming unique artificial habitats for a myriad of marine organisms, where fish can yield the highest biomass (Claisse *et al*., 2014; Torquato *et al*., 2018; Meyer-Gutbrod *et al*., 2019; van Elden *et al*., 2019; Coolen *et al*., 2020; Lemasson *et al*., 2021). The termination of operation and dismantling of the jacket structure is part of the decommissioning phase, where five primary decommissioning strategies exist for coastal oil platforms: i) leaving the platform in place, ii) complete removal of the structure (inevitably leading to the elimination of the epibenthic and associated fauna); and the so-called "reefing" alternatives which includes iii) topping (top portion removed to > 20 m subsurface and lower portion remains standing), iv) toppling (platform toppled over in same location), and v) relocation followed by toppling (Bull, Love, 2019).

Oil platforms provide numerous ecosystem services since they function as artificial reefs, harbouring complex ecological communities that most time include species of commercial interest (Ajemian *et al*., 2015; McLean *et al*., 2019; Todd *et al*., 2021; van Elden *et al*., 2022). These platforms also provide opportunities for ecotourism activities such as marine wildlife watching, spearfishing, and recreational diving (Shani *et al*.,

2012; Lemasson *et al*., 2021). Because of their significant ecological, fishing, and tourism potential as "novel" ecosystems, globally, there is pressure to recognise and highlight the ecological and economic value of standing platforms and thus opt for alternative strategies other than complete removal during the decommissioning phase (van Elden *et al*., 2019; Lemasson *et al*., 2021). When permitted, these platforms are popular sites for recreational and artisanal fishing (Dugas *et al*., 1979; Jablonski, 2008). An illustrative example of the overlap between habitat provision, ecotourism, and fishing activities was the decommissioned oil rig MX-1, located 3 km off the coast of Los Órganos, Piura (Jacinto *et al*., 1996), lying on the seafloor at a maximum depth of 60 m. Around the MX-1, local artisanal fishermen would employ traditional rafts called "tumpis", declared as cultural heritage (Hooker, Ubillus, 2011; MINCUL, 2018).

Globally, previous research on platform-associated fauna has predominantly focused on biofouling (benthic) assemblages according to Coolen *et al*. (2020), and ichthyofauna (Seaman *et al*., 1989; Fabi *et al*., 2004; Consoli *et al*., 2013; Torquato *et al*., 2018; Schulze *et al*., 2020; Todd *et al*., 2021; Sih *et al*., 2022; Tothill *et al*., 2024). Such studies are scarce or unreported along the Peruvian coastline, with only one accessible study (Hooker, Gonzales, 2012). Constituting 19% of west South America, the Peruvian coastline (> 3000 km from 3.5–18°S) is characterised by intensive coastal upwelling which, coupled with various environmental and biological factors, contributes significantly to the high productivity of the Peruvian marine ecosystem (Zuta, Guillén, 1970; Gutiérrez *et al*., 2016; Ibanez-Erquiaga *et al*., 2018). The upwelling processes increase nutrient availability, fostering large biomass, and therefore large-scale fisheries (Chavez *et al*., 2008). The northern Peruvian coast harbours 70% of Peru's marine biodiversity (Hooker, 2009; Hooker *et al*., 2011; Hooker, Ubillus, 2011). This regional diversity is distributed along two distinct biogeographic zones: the Panamic Province (22°N–4.5°S), the Peruvian Province (5.5°–42° S) (Spalding *et al*., 2007; Chaigneau *et al*., 2013; Hooker *et al*., 2013; Ibanez-Erquiaga *et al*., 2018; Vermeij et al. 2024); with a transition zone (ecotone) in between (~4.5–6°S) (Fig. 1). The coastline of Piura region in northern Peru spans around 400 km (4.08–6.38°S) where 90 jacket-type oil rig structures in different operational stages (exploration, exploitation, or abandonment) rest on the seafloor.

Due to the limited baseline information for ichthyofauna associated with artificial reefs in the Tropical Eastern Pacific, this study aimed to assess the composition and vertical structure of the fish associated with the oil platform MX-1, during the austral spring of 2022. Our study also aimed to determine whether the vertical structure of the platform provided favourable conditions for hosting fish species from various biogeographical regions, and also explore the role of the oil rig as a biodiversity facilitator with potential indirect benefits to users of the sea including artisanal fishermen and ecotourism agencies.

MATERIAL AND METHODS

Study area. The decommissioned platform MX-1 was located 3 km off the coast of Los Órganos, Piura, Peru (4.16°S, 81.16°W), next to the recently established Reserva Nacional Mar Tropical de Grau (Fig. 1) (Cutipa-Luque *et al*., 2020; MINAM, 2023, 2024a). This region lies at the confluence of the Panamic and transition zones, influenced by the interaction of the cold, nutrient-rich Humboldt Current from the south, and the warm Equatorial Counter current from the north, driving high productivity and seasonal oceanographic variability. The regional climate is semi-arid. Rainfall is typically low, except during El Niño episodes, which significantly alter oceanographic conditions, mixing much warmer, more oxygenated and less nutrient-rich waters (Escribano *et al*., 2004; Guevara, Milla, 2007). The platform was a 65 m high metal structure with seven levels, six of which were submerged at depths of 5, 15, 26, 37, 49, and 60 m of sea water (Petro-Tech, 2009). The platform provided complex hard-substrate habitats in an area dominated by soft-bottom sediments. Removal operations using the topping strategy began in 2023 in accordance with Directorial Resolution R.D. N°079-2022-MINEM/DGAAH (MINEM, 2022).

Underwater visual censuses. Six open-circuit SCUBA dives were carried out over six days during austral spring (October 2023). The structure was vertically divided *a priori* into five depth strata/ranges: 0–5 m, 5–10 m, 10–20 m, 20–30 m, and 30–40 m (as described by Hooker, Gonzales, 2012; Todd *et al*., 2018). Due to safety reasons in diving procedures (*e.g*., avoidance of 'deep-air diving') and logistical constraints, the deepest strata between 41–60 m was not surveyed. The descent was made along the outer periphery of the platform to prevent disturbing fish on the way down. The deepest stratum 30–40 m was surveyed first (Pyle, 2019) in such a way that the bottom time at maximum depth did not reach the no-decompression limit (NDL 8 min at 42 m) (PADI RDP recreational dive planner table). The visual census adopted the roving-diver survey technique by Rassweiler *et al*. (2020), a way to rapidly sample the entire fish assemblage at any given site, recording all fish encountered where divers swam slowly from vertical pilings, conducting a square sweep within the structure and gradually ascending while observing the fish associated with the substrate and the water column. The area delimitation was adapted from the fixed-point methodology considering a field-of-view of ~6 m^2 approximately where fish were identified and counted accordingly (Cappo *et al*., 2006; Hooker, Gonzales, 2012; Lindfield *et al*., 2014; Thurstan *et al*., 2014; Caldwell *et al*., 2016). Five replicate counts were conducted per depth stratum, resulting in a total estimated surveyed area of ~150 m^2. Supporting footage recordings were taken with a GoPro Hero 6 action camera and two SOLA 2000-lumen video lights. Data collection was supported by a visual record of identification and abundance recommended by Seaman *et al*. (1989) and Rilov, Benayahu (2000). All dives were logged accordingly using the SciDive record forms proposed by Moreno (2020). The species identification was cross-validated by revisiting the supporting footage and using relevant literature (Chirichigno, Veléz, 1998; Humman, DeLoach, 2003; Robertson, Allen, 2015; Siccha-Ramirez *et al*., 2022; Fricke *et al*., 2018) and consultation with ichthyologists with experience on the ichthyofauna of the region. Once identification and counts were validated, the abundances were tabulated and organised by species and depth.

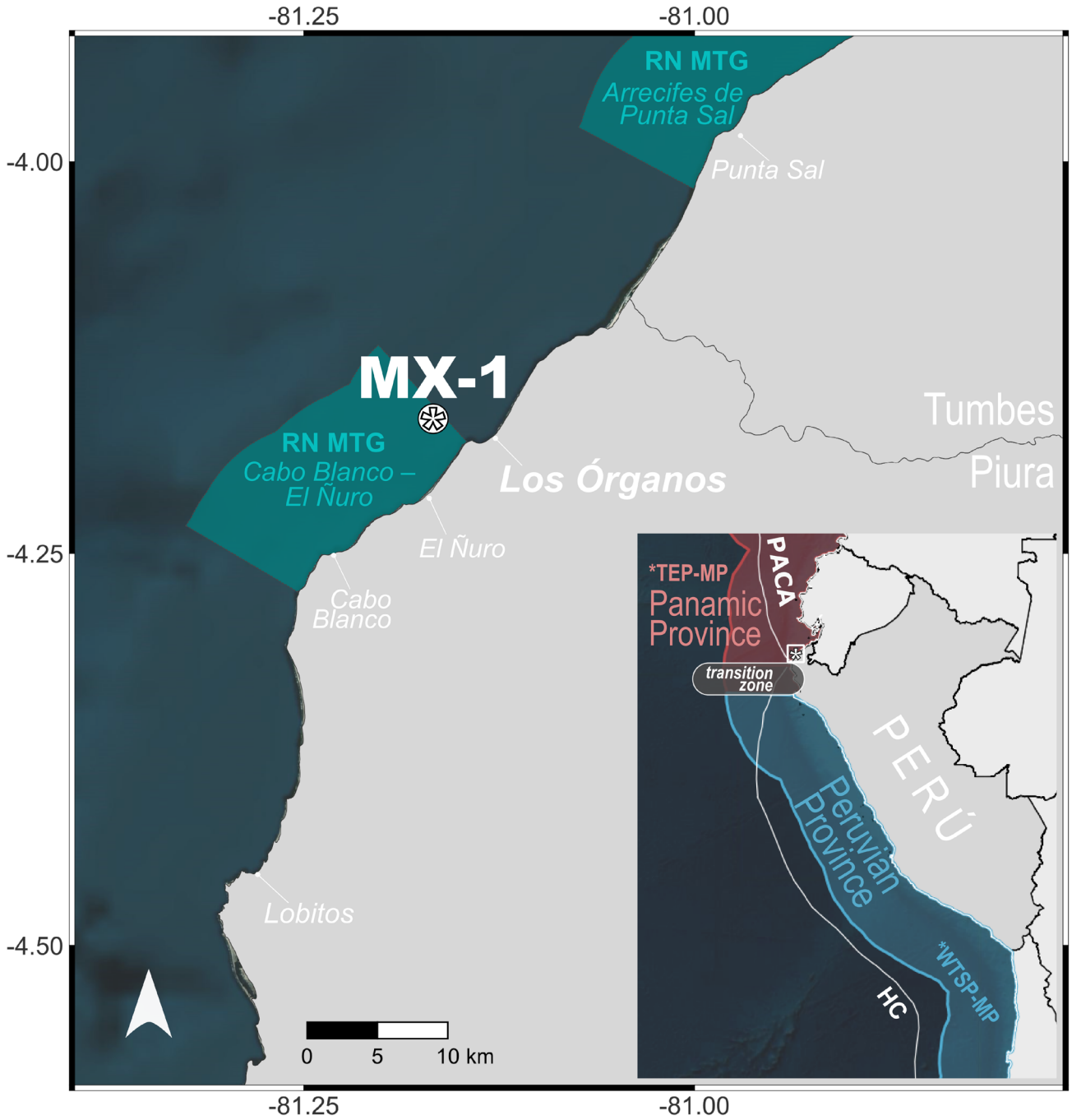

FIGURE 1 | Study area off the northern coast of Peru in the southeastern Pacific. The decommissioned MX-1 platform was located approximately 3 km offshore from Los Órganos, Piura, Peru (4.16° S, 81.16°W), adjacent to the recently established *Reserva Nacional Mar Tropical de Grau* (RN MTG; Cabo Blanco–El Ñuro polygon). The inset map shows the boundaries of two Large Marine Ecosystems (LMEs): the Pacific Central American Coastal LME (PACA) LME and the Humboldt Current (HC) LME. Also depicted are the two marine biogeographic provinces and the transitional ecotone (~4.5–6°S) referenced in the text: the Panamic Province (22°N–4.5°S, also referred to as the Tropical Eastern Pacific Marine Province, TEP-MP), and the Peruvian Province (5.5°–42°S, also known as the Warm Temperate Southeastern Pacific, WTSP-MP). Polygons of the RN MTG were obtained from https://geo.sernanp.gob.pe/visorsernanp/, marine regions from https://www.marineregions.org/, and country polygons from https://earthworks.stanford.edu/catalog/. Map produced in QGIS 3.28.12.

Fish assemblage diversity indices and functional strategies. Fish abundance and alpha diversity were calculated per depth strata. To describe the fish diversity in terms of richness, Margalef's (1958) index was used. Other indices including Shannon-Weaver (Shannon, Weaver, 1949) and Pielou's evenness (Pielou, 1981) were employed to compare fish assemblages between depths. The Chao-1 index was used to estimate total species richness (S_{est}) and compared it with the observed (S_{obs}) (Chao, 1984; Chao *et al*., 2014). The SIMPER (similarity percentage) routine was applied to identify which taxa were primarily responsible for the observed differences between groups of samples (Clarke, 1993). To identify spatial variation in species composition beta diversity as proposed by Whittaker (1960) was used. Additionally, a cluster analysis was employed using Sorensen dissimilarity distance (Sorensen, 1948). All calculations were done in PAST 4.12 (Hammer *et al*., 2001). The functional strategy of each species or taxon was described using five categorical traits based on the feeding and locomotion of species, namely: body shape, swimming type, diet, habitat, and trophic niche; all of which are crucial for determining their role in the marine ecosystem (modified from Torquato *et al*., 2018; Froese, Pauly, 2023). Descriptions of each categorical trait are provided in Tab. 1. Abundance data were log-transformed to meet the assumptions of normality, which was evaluated through a quantile-quantile (q-q) plot of residuals and the Shapiro-Wilk test, while homogeneity was assessed through residual *vs*. predicted values plot. One-way PERMAVOVA was used to identify differences among depths. Non-metric multidimensional scaling (nMDS) was used to represent the pairwise dissimilarity of fish assemblage between depths in a two-dimensional space. Statistical analyses were computed using the software PAST 4.12 (Hammer *et al*., 2001).

Oceanographic data. Temperature and salinity along the water column were obtained with a hand-held SonTek CastAway-CTD attached to the diver's harness D-ring during the dive (ACT, 2007; Patterson *et al*., 2011). Based on these casts, the predominant water masses were identified following the classification of Zuta, Guillén (1970).

TABLE 1 | Functional traits of fish species analysed for their ecological roles and strategies.

Trait	Description
Body shape	Describes the physical form and structure of the fish, which can influence hydrodynamics, manoeuvrability, and energy efficiency.
Swimming type	Refers to the method of locomotion used by the fish.
Diet	Details the feeding habits of the fish. Diet influences the fish's role in the ecosystem and its interactions with other species.
Habitat	The environment where the fish lives.
Trophic niche	The role of the fish in the food web.

RESULTS

Zonation of fish assemblages: abundance, richness, and diversity. Overall, a total of 7,969 fish were counted, which belonged to 27 species distributed within 13 families. Among these, eight (30%) commercially targeted species were recorded (Tab. 1). The Pomacentridae, Serranidae, and Carangidae were the richest families with five species each, followed by Blenniidae with three species. Fish were mostly aggregated between the crossbeams and pilings of the rig (Figs. 2, 3).

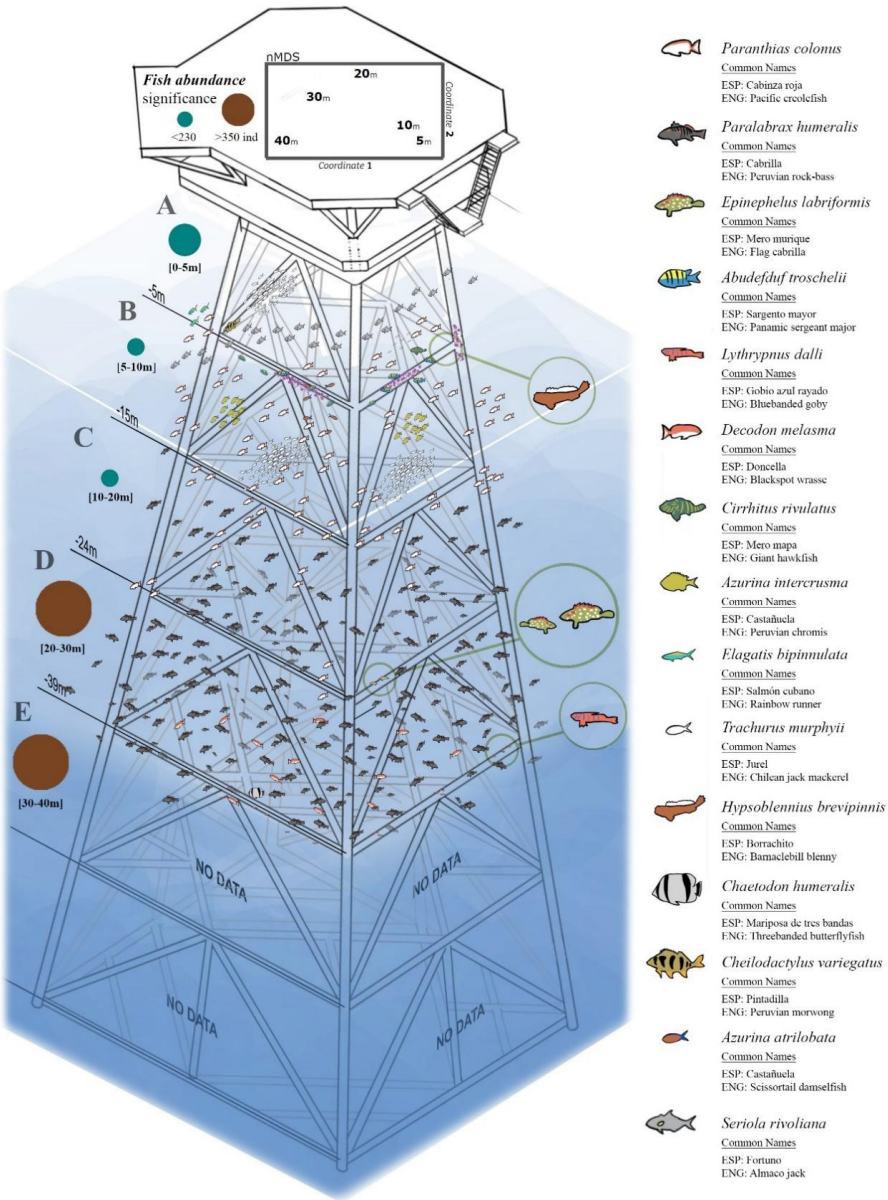

FIGURE 2 | Schematic of the MX-1 oilrig depicting the vertical distribution of fish according to the surveyed depth strata. Also shown are the relative dominance of the ichthyofauna and nMDS calculated from the survey observations (austral spring, October 2022). One-way PERMANOVA showed a significant difference in fish composition which is represented by letters.

FIGURE 3 | Dominant species around MX-1. **A.** Peruvian rock seabass *Paralabrax humeralis*, **B.** Pacific creole-fish *Cephalopholis colonus* (n=261) was most abundant between 10–20 m, actively swimming against the current in search of food and exhibiting reproductive behaviour, **C.** school of Chilean jack mackerel *Trachurus murphyi*, **D.** Longfin yellowtail *Seriola rivoliana*, **E.** Peruvian rock seabass *Paralabrax humeralis* (n=761) dominated between 30–40 m depth forming dense aggregations among the structure's pilings, **F.** Panamic sergeant major *Abudefduf troschelii* (n=80) was mainly observed at 5 m depth associated with the most diverse substrate where it coexisted with a variety of other reef fish species near crossbeams.

Species dominance varied according to depth strata. The most abundant taxa were the Peruvian rock seabass *Paralabrax humeralis* (Valenciennes, 1828) (n = 761), the Pacific creole-fish *Cephalopholis colonus* (Valenciennes, 1846) (n = 261), the Panamic sergeant major *Abudefduf troschelii* (Gill, 1862) (n = 80), the Chilean jack mackerel *Trachurus murphyi* Nichols, 1920 (n = 73), and the longfin yellowtail *Seriola rivoliana* Valenciennes, 1833 (n = 21) (Fig. 3). The shallowest stratum (5 m) showed the highest taxonomic richness (n = 19) (Fig. 2) (Tab. **S1**), while the two deepest strata (20–40 m) showed the highest abundance with 351 and 442 counts, respectively. In terms of biogeographic affiliation, 20 species belonged to the Panamic Province, three to the Peruvian Province, and the remaining four are commonly distributed in both provinces. The Equatorial Surface Water (ESW) and Cold Coastal Water (CCW) were identified from the average oceanographic vertical profile, including temperature and salinity (Tab. **S2**).

The nMDS based on fish composition showed a vertical zonation in fish composition, that is, a clear separation by depth, although the two shallowest strata (0–10 m) were the most similar (Fig. 2). Beta diversity indicated a differentiation between fish composition along the water column (Tab. **S3**). Sorensen clustering showed a relationship among 5–10 m and 20–30 m (Fig. **S4**). The dominance of *P. humeralis* was recorded between

20–40 m, while *C. colonus* was dominant between 5–20 m (Tab. **S5**). The epibenthic fish assemblages were dominated by different species depending on the depth strata (Fig. 2). The number of species was lower as depth increased, indicating that the shallower strata supported a greater number of species. The total number of individuals and dominance was higher with increasing depth; thus, evenness and equitability were higher at shallower depths, suggesting a more even distribution of abundance among species. Shannon and Margalef diversity indices exhibited a downward trend as depth increased, with the highest diversity at 5 and 20 m, suggesting that the assemblage composition was more heterogeneous towards the shallows. The estimated species richness using the Chao-1 index tended to increase with decreasing depth, suggesting that there may be more species present than observed directly at all depth strata. The alpha diversity and beta indices results are shown in Tabs. **S1**, **S3**.

Functional strategies. Most species were carnivorous (n = 14), followed by omnivores (n = 6) and planktivorous (n = 4) (Tab. **S6**). Carnivores were numerically dominant at all depths, with higher dominance at the deepest range surveyed (30–40 m), where other groups were scarce. Both carnivores and omnivores had a higher number of species observed from 5–20 m. Fish that feed on sessile invertebrates, such as the three-banded butterflyfish *Chaetodon humeralis* Günther, 1860, were only recorded at 40 m. Planktivorous fish were found across all surveyed depth ranges. The highest trophic niche belonged to the longfin yellowtail *S. rivoliana* (4.5 ± 0.7), while the lowest (2.0 ± 0.0) was shared by three species: the beau brummel *Stegastes flavilatus* (Gill, 1862), the brassy chup *Kyphosus vaigiensis* (Quoy & Gaimard, 1825), and the barnaclebill blenny *Hypsoblennius brevipinnis* (Günther, 1861). The distribution of swimming types among these species is detailed in Tab. **S7**. The observed swimming patterns reflected functional strategies related to habitat occupation and feeding. Most species exhibited subcarangiform swimming, predominantly among carnivores and omnivores inhabiting mid and deep waters. Carangiform and labriform behaviours were displayed by species from different trophic levels and habitats, while *Chaetodon humeralis*, the only species exhibiting balistiform swimming, was exclusively recorded at 40 m, aligning with its feeding preference for sessile invertebrates. These differences in locomotion may influence the vertical distribution of species and their ecological roles within the assemblage structure.

DISCUSSION

Fish diversity and habitat conditions. Globally, numerous studies have extensively documented the composition of ichthyofauna associated with oil rigs (Barker, Cowan, 2018; Torquato *et al*., 2018; Bull, Love, 2019; Love *et al*., 2019; McLean *et al*., 2021). The submerged sub-structures of the oilrigs which include crossbeams, vertical pilings, and cryptic habitats such as crevasses enhance habitat complexity, potentially leading to high diversity and abundance in reef fish populations (Friedlander *et al*., 2014; Bull, Love, 2019). Standing decommissioned platforms, typically host higher species richness compared to toppled and cut-off structures (Bull, Love, 2019). Recent research efforts continue to investigate the role of oil platforms as artificial reefs and their impact on

fish diversity. Nevertheless, the effect of these structures varies across different oceanic regions, influenced by unique environmental and ecological conditions. For example, between 12 to 26 fish species were identified in three oil rigs further north MX-1, where the scissortail damselfish *Azurina atrilobata* Gill, 1862 and the Pacific creole-fish *C. colonus* were the most abundant (Hooker, Gonzales, 2012). Our study identified and reported the vertical zonation of fish assemblages, the dominance of *C. colonus*, and 16 species in common with the abovementioned study, primarily associated with the Panamic region. This can be attributed to similar oceanographic and habitat conditions in both study areas. Specifically, platform MX-1, which was located further south with greater depth, may facilitate the colonisation of species affiliated with the Peruvian and Panamic regions. This facilitated the recruitment of a greater diversity of species, even under fishing pressure. The occurrence of commercial species across multiple oil platforms indicates that these taxa are not confined to a single location (Hooker, Gonzales, 2012), suggesting broader adaptability to various marine environments. The richness of fish taxa around oil rigs can be different depending on the marine region, for instance, 41 fish taxa have been recorded in the Mediterranean Sea (Consoli *et al*., 2013), 40 species in oilrigs off southern California (Helvey, 2002), and 83 species associated to the Al Shaheen oil field in the Persian Gulf (Torquato *et al*., 2018).

Surveys around Australian oil rigs have identified critically endangered species, unique fish behaviours, potential new fish species, and diverse assemblages, comprising a total of 117 fish taxa (McLean *et al*., 2021). In contrast, our study identified only 27 species, indicating a comparatively lower richness than reported for similar structures worldwide. This difference may reflect regional biogeographic patterns, the limited temporal extent of data collection, and methodological constraints. Natural rocky reefs in the area have reported up to 82 fish species, representing a highly diverse assemblage (Zavala *et al*., 2025). In contrast, kelp forest ecosystems, characteristic of the Peruvian upwelling system, have recorded 25 fish species (Cuba *et al*., 2022). Furthermore, Isla Foca, the closest island further south to the study site, hosts 43 fish species (Hooker *et al*., 2012). Compared to these ecosystems, the 27 species documented at MX-1 suggest an intermediate richness level. Although lower than the diversity found in rocky reefs and Isla Foca, the artificial structure hosted more species than temperate kelp forest habitats at higher latitudes in Peru. Highlighting its potential role as a complementary habitat within the local seascape. According to the Chao1 index, the estimated taxa richness (S_{est}) could be as high as 55 (twice the S_{obs}), which would represent 45% of the 82 species of coastal fish richness reported in marine rocky reefs near the zone (Zavala *et al*., 2025).

Recent research along the central coast of Peru reported 18 fish species associated with an artificial port terminal, revealing a vertical stratification in fish distribution and a predominance of carnivorous species across depth zones (Pacheco *et al*., 2023). Among them, key commercial species such as the lorna drum *Sciaena deliciosa* (Tschudi, 1846) were identified, reinforcing the role of artificial structures in attracting valuable biological resources. These findings also suggest possible fish movements between natural and artificial habitats (Caldwell, Gergel, 2013), underscoring the importance of further research into connectivity, ecological function, and implications for fisheries management.

The Peruvian rock seabass *P. humeralis* and the Pacific creole-fish *C. colonus* exhibited depth-dependent variations (Fig. 2). These patterns closely align with thermal gradients,

as temperature generally decreases with depth, influencing key physiological aspects such as metabolism, growth, and behaviours including reproduction and aggregation (O'Gorman *et al*., 2016; Boltaña *et al*., 2017; van Denderen *et al*., 2020). Such vertical distribution likely reflects a behavioural response to both the physical stratification of the water column (Coles, Tarr, 1990; Martin, Lowe, 2010) and biological aspects such as prey availability (Torquato *et al*., 2018). Traditionally, this pattern is attributed to reduced energy availability, increased pressure, and lower temperatures with greater depth. However, the expected relationship between richness and depth may also be influenced by higher photosynthetic production rates in the uppermost layers (Torquato *et al*., 2018; Harvey *et al*., 2021).

Biogeographic affiliations. The MX-1 oil platform was located between the Panamic Province and the transition zone of the Tropical Eastern Pacific, a region shaped by the dynamics of the Humboldt Current and ENSO variability (Ibanez-Erquiaga *et al*., 2018; Hooker, 2009; Brochier *et al*., 2013). We identified 23 reef fish species that were using the platform as habitat, including 20 from the Panamic Province and 3 from the Peruvian Province. This suggests MX-1 acted as a refuge of biogeographical connectivity, supporting ichthyofauna species from both northern and southern assemblages. Intriguingly, the different phases of El Niño Southern Oscillation (ENSO) introduce dynamicity to the distribution of the species, potentially modulating community composition across planktic, benthic, and specifically, fish biota (Tarazona *et al*., 2003; Hooker, 2009; Miloslavich *et al*., 2011).

The reported occurrence of *Chirodactylus variegatus* (Valenciennes, 1833), 150 km north of its previously reported range (Chirichigno, Vélez, 1998), may be associated with La Niña negative anomalies condition during 2022 (ICEN = -1.39) (Li *et al*., 2022; MINAM, 2024b). Similarly, the abundance of *P. humeralis* has shown sensitivity to ENSO phases (Adams, Flores, 2016), underscoring the importance of monitoring indicator species. By systematically recording fish assemblages and monitoring the abundance of identified indicator fish species in artificial reefs in the Tropical Eastern Pacific, we can discern the impacts of ENSO phenomena on the dynamics and management of fisheries' target species.

Physical oceanographic processes influence the distribution of fish larvae across various spatial scales (Victor, Wellington, 2000; Green *et al*., 2015; Álvarez-Noriega *et al*., 2020). While our study did not assess larval dispersal, the high abundance of juvenile individuals of commercially targeted species observed around the platform suggests that artificial structures may play a role in local recruitment dynamics. Previous studies have indicated that offshore platforms can act as focal points for larval settlement and potential sources of ecological spillover, *i.e*., outward net emigration of juveniles, subadults and adults from the protected areas (Love *et al*., 2006; Buxton *et al*., 2014; Pondella *et al*., 2015). However, without ichthyoplankton surveys or biophysical dispersal models, the extent to which the platform influenced larval transport in the study area remains uncertain. Future research incorporating such methodologies would provide valuable insights into the role of artificial structures in larval retention and dispersal along the Peruvian coast.

Oil rigs have been reported to work as a driver to smooth the dispersion and colonisation of fish by increasing the availability of preferred habitats and ecological

connectivity within the populations (Mclean *et al*., 2022; Watson *et al*., 2023). Oil platforms such as MX-1 may potentially enhance connectivity across seascapes by facilitating vertical and horizontal fish movement, as has been documented in other regions where thermoclines and local currents influence fish dispersal (McLean *et al*., 2022). These structures have been shown to provide suitable habitat for both adult and juvenile fish, potentially supporting fish communities independent of nearby natural reefs (Torquato *et al*., 2018). Similarly, artificial structures might influence benthopelagic coupling (Reeves *et al*., 2018) and nutrient transfer (Layman *et al*., 2013), though these dynamics remain to be evaluated in the MX-1 and similar areas. Nevertheless, it is crucial to evaluate the ichthyofauna composition from shores, tidal pools, subtidal rocky reefs, and artificial structures near the sampling area to identify habitat links and connectivity in the surrounding region. The study of oceanographic factors and larval dispersion may largely explain the fish diversity recorded in the present study, but further research is needed to understand the larger scale and dynamic of a set of oil rigs as a complex structure fish aggregation for management (Snodgrass *et al*., 2020).

Feeding and behavioural habits. Fish assemblages at MX-1 displayed clear depth-related patterns, likely influenced by structural complexity and resource distribution across the water column. The presence of herbivores between 5–20 m could be related to the vertical distribution limits of phototrophs such as macroalgae (Raven, Hurd, 2012). Therefore, the effect of light penetration may be reflected in the vertical distribution of herbivorous fish, which are rare in deeper layers (Torquato *et al*., 2018). Juvenile kyphosids, which feeds on macroalgae, appear to remain pelagic (Leis, Carson-Ewart, 2000) dispersing by rafting (Paulay, Meyer, 2006; Casazza, Ross, 2008), crossing oceanic barriers (Pfaller *et al*., 2019) and arriving to reef-like habitats like oil rigs. MX-1 provided fish with greater access to planktic food sources from all levels of the water column near the shelter of the platform structure (Harvey *et al*., 2021). Additionally, schooling planktivores (*e.g*., *Abudefduf*, *Azurina*, and *Chromis*) were observed between 5–30 m, often displaying coordinated movement patterns (Pavlov, Kasumyan, 2000). Carnivores such as Cirrhitidae family (hawk-fishes) are usually found on the reef substrates, which offer them protection against predators and a strategic spot for hunting small fish and invertebrates (Hooker, 2009; Schmitt *et al*., 2009) (Fig. **S8**). The density of the scorpaenids was greater in the pilings, which extend until 20–40 m depth of the structure. A similar pattern was reported in the Northern Adriatic Sea, where the occurrence of scorpaenids may be related to either prey availability or a suitable habitat (Scarcella *et al*., 2011). We hypothesise that the pilings and crossbeams change the water flow and intensity of the currents, favouring fish to catch food (Fernández-Álamo, Färber-Lorda, 2006). Also, the high availability of food resources like plankton, invertebrates, and fish could be one of the main reasons behind the observed dominance of carnivorous fish around the MX-1 as reported in Qatari waters (Torquato *et al*., 2018). The hard substrate of the submerged platform provided habitat for erect flexible sessile invertebrates which increases the substrate rugosity and provides suitable space for motile invertebrates and small fish feeders such as three-banded butterfly *C. humeralis* (Dominici-Arosemena *et al*., 2005; Layman, Allgeier, 2020). The diverse swimming behaviours exhibited by fish associated with the oil platform showcase a range of adaptations and locomotive strategies within this ecosystem (Blake, 2004).

The abundance of cryptic species, such as blennioids and gobiids (Fig. **S8**), might be underestimated due to the limitations of the established methodology. Our main focus were pelagic and benthopelagic species, therefore we used wide-angle cameras for footage acquisition. Implementing methodologies focused on cryptic fish (Bessey *et al*., 2023) could allow us to reach the estimated richness and abundance of fish assemblages in oil platforms, however, it would require extending the surveying bottom-times and scientific divers dedicated on cryptic species. A potential solution to the former problem and, at the same time, for surveying deeper strata, would be implementing different decompression strategies to extend bottom times, reduce narcotic effect, and accelerate decompression. Such would be the utilisation of standard gases as a technical diving strategy. For instance, to keep an equivalent narcotic depth of ~30 m, enriched air nitrox (EANx32) could be used instead within the 0–30 m range. Alternatively, deeper ranges could be surveyed by adding helium to the mix: trimix 21/35 (30–45 m) or trimix 18/45 (45–60 m). These alternatives would require switching to EANx50 as decompression gas at 21 m during the ascent to reduce deco-times (Doolette, Mitchell, 2013; Mitchell, Doolette, 2013; Walker, 2021).

The presence of the observers can affect fish behaviour, for example, altering the swimming patterns (Scarcella *et al*., 2011). Fish avoid divers due to the sound of bubbles produced by open circuit SCUBA (Lindfield *et al*., 2014). Our presence perturbed some fish species such as the starry grouper *Epinephelus labriformis* (Jenyns, 1840), the large-banded blenny *Ophioblennius steindachneri* Jordan & Evermann, 1898, and the threadfin bass *Pronotogrammus multifasciatus* Gill, 1863. Additionally, some fish showed perturbed behaviour as a reaction to the video lights during the survey between 30–40 m, making it more difficult to identify them. Contrastingly, the Pacific creole-fish *C. colonus* was rather attracted to the bubbles emitted by the open circuit divers. Authors have shown that surveying with alternative methodologies such as using close circuit rebreathers (CCR) and remotely operated vehicles (ROV) are effective for estimating the community structure of fish, the spatial distribution of individuals, and functional diversity (Lindfield *et al*., 2014; Ajemian *et al*., 2015; de Juan *et al*., 2015; Torquato *et al*., 2018; Tothill *et al*., 2024). In the Gulf of Mexico, more efficient assessments of reef-associated fish communities using side-scan sonar methodology were possible. Correlating hydroacoustic images and oceanographic data can be used to answer macroscale questions otherwise more difficult with visual methods (Bollinger, Kline, 2017). Further research should consider which methodology adapts better to established research objectives, but all this depends on the aims of the study and the logistical capabilities of the surveyors.

Decommissioning or ecosystem services. Although the installation and operation of exogenous man-made structures cause deleterious impacts on benthic communities and surroundings (Chen *et al*., 2024), once established, reef-like habitats such as oil rigs can increase the local fish abundance and act as fish aggregation devices (FAD) (Bull, Love, 2019). Depending on the accessibility, these fish aggregations can further be exploited by fishermen and recreational spearfishers (Fig. **S9**) (Polovina, 1991; Kingsford, 1999; Snodgrass *et al*., 2020). Nevertheless, increased fishing pressure around these structures may therefore contribute to the decrease of fish stocks in the long run if not managed properly (Jagerroos, Krause, 2016; Bull, Love, 2019;

Castagnino *et al*., 2023). Artificial reefs provide shelter from strong currents, and food resources for consumers, conform sites for reproduction, feeding, and nursery; and supply substrate for reef-associated organisms (Jagerroos, Krause, 2016). Having identified eight commercial species (Figs. 2, 3, **S9**), we highlight the capacity of the habitat to host species of commercial interest, suggesting that MX-1 was contributing to fisheries stock productivity, as reported for oil rigs further north in Tumbes, and other regions of the world (Durand, Seminario, 2009; Hooker, Gonzales, 2012; Barker, Cowan, 2018; Clarke *et al*., 2021; Harvey *et al*., 2021; Mclean *et al*., 2022). The ecosystem services provided by MX-1 were evident, and as reported for many other oil rigs: food provision, animal genetic resources, ecological connectivity (*e.g*., larval dispersal), and recreational activities (MEA, 2005; Jagerroos, Krause, 2016; Villéger *et al*., 2017; Sommer *et al*., 2019; Lemasson *et al*., 2021; Watson *et al*., 2023).

During the decommissioning phase, an oil rig can be completely removed, turning the underneath seafloor back to its unobstructed prelease condition (Bull, Love, 2019). Complete removal of a platform will likely eliminate most fouling biomass, and displace associated mobile fauna, mainly fish (Pondella *et al*., 2015), therefore impacting on the biological resources and ecosystem services that had been formed (Jagerroos, Krause, 2016). The decommissioning order to remove the standing oil rig MX-1, included as part of the closure of Lote Z-2B, was emitted through the Directorial Resolution R.D. N° 079-2022-MINEM/DGAAH (MINEM, 2022), and the topping strategy was applied. In March 2025, the Superior Court of Justice of Lima (Peruvian Judiciary) issued a belated appeal for protection i) recognising the role of MX-1 as an artificial reef to be considered as an area special protection, ii) rendering the decommissioning plan null and void, iii) ordering the emission of a general normative framework for the protection of artificial reefs (Corte Superior de Justicia de Lima, 2025). Although it was an important legal precedent, the ruling no longer prevented the topping action from occurring. The removal of the upper layers of MX-1 arguably disrupted the vertical zonation observed along the platform, potentially reducing the trophic connectivity throughout the water column. This alteration may have led to declines in biomass and biodiversity associated with the platform, compromised the integrity of the food web already developed, and impaired ecosystem functioning. As a result, the fish community surrounding the remaining structure may shift toward dominance by carnivorous species associated with deeper layers like *P. humeralis* and *P. multifasciatus*, potentially resulting in a simplified and less resilient ecosystem. The remnants of "Piedra Redonda", a topped oil rig found further north in Tumbes (3°S), are found only below 50 m of sea water. Above it, very strong mid-water currents (0–20 m) occur, and no fish can be found along the first 45 m of depth (BM, pers. obs.). Although topped at shallower depths (below ~20 m of sea water), similar patterns could be expected to be found in the current situation of MX-1 such as higher current speeds and devoid of fish.

A minimum threshold for environmental, technical, societal and economic risks needs defining when making decisions regarding the decommissioning pathways and strategies (Watson *et al*., 2023). However, considering the aspects mentioned so far, the removal action ignored the ecological value of MX-1 and the opportunity to manage it under a "rig-to-reef" approach (*i.e*., converting confiscated platforms into artificial reefs, taking advantage of the ecosystem services provided by the structure which generates social and ecological compensation) (Fowler *et al*., 2014; Henrion *et al*., 2015;

Bull, Love, 2019; Sommer *et al*., 2019; Lemasson *et al*., 2021). Fishing and diving around rigs are a major component of the local tourism industry. Artisanal fishermen, sport fishers, and recreational divers generally support rigs-to-reefs programs, which in turn creates hundreds of jobs (Stanley, Wilson, 1989; Frumkes, 2002; Jagerroos, Krause, 2016; van Elden *et al*., 2019).

The decommissioned standing oil rig MX-1 functioned as an effective fish aggregation device (FAD). The surveyed 150 m^2 were habitat for numerous fish aggregations, including species of commercial importance. Among the eight commercially targeted fish species identified during the survey, the Chilean jack mackerel *T. murphyi* was the most important pelagic species for Peruvian fisheries (Csirke, 2013). Our research confirmed a vertical zonation of fish assemblages around the decommissioned oil platform MX-1. The removal might impair the system that had been formed during its operational and abandonment phases including the fish populations that depended on the platform. Our study contributes to the understanding of the ecological role of artificial reefs in the marine environment in northern Peru (Tropical Eastern Pacific). This work also represents a valuable precedent case-study for timely implementing special protection schemes in other oil rigs yet to go through decommissioning phases. A key question persists: upon the removal of the MX-1 oil rig, where did the fish biomass relocate to? and how did the marine space change in the absence of this artificial reef?

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AUTHORS' CONTRIBUTION

Diego Cuba: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing-original draft, Writing-review and editing.

Bernabé Moreno: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing-original draft, Writing-review and editing.

ETHICAL STATEMENT

This study was conducted in accordance with ethical guidelines, following approval by the institutional Ethics Committee (approval No. 040-CIEI-AB-CIENTÍFICA-2022).

DATA AVAILIBILITY STATEMENT

The datasets generated during the current study are available in the Figshare repository, https://doi.org/10.6084/m9.figshare.29367722.

COMPETING INTERESTS

The authors declare no competing interests.

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