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An acoustic-optic comparison of fish assemblages at a Rigs-to-Reefs habitat and coral reef in the Gulf of Thailand

Edward C.P. Sibley [a,b,*], Alethea S. Madgett [b,c], Travis S. Elsdon [d,e], Michael J. Marnane [d], Euan S. Harvey [e], Se Songploy [f,g], Jes Kettradad [f,g], Paul G. Fernandes [h]

[a] School of Biological Sciences, King's College, University of Aberdeen, Aberdeen, United Kingdom
[b] The National Decommissioning Centre, Newburgh, Aberdeenshire, United Kingdom
[c] School of Engineering, University of Aberdeen, Aberdeen, United Kingdom
[d] Chevron Technical Centre, Perth, WA, Australia
[e] School of Molecular and Life Sciences, Curtin University, Bentley, 6102, WA, Australia
[f] Aquatic Resources Research Institute, Chulalongkorn University, Bangkok, Thailand
[g] Marine Ecology and Utilization of Marine Resources Research Unit, Chulalongkorn University, Bangkok, Thailand
[h] The Lyell Centre, Heriot-Watt University, Research Avenue South, Edinburgh, EH14 4AP, United Kingdom

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ABSTRACT

The number of decommissioned oil and gas platforms will increase over the coming decades. In the tropics and sub-tropics, platforms may operate near biodiverse natural habitats, such as coral reefs. Abundant and diverse fish communities often aggregate around platforms, with different decommissioning options posing variable ecological effects on these assemblages. One decommissioning option is to repurpose platforms into artificial reefs, a process commonly termed "Rigs-To-Reefs" (RTRs). Many RTR programs attempt to retain or enhance habitat availability and associated fish assemblages. To help demonstrate the importance of RTR projects, the fish habitat value of RTRs can be estimated by comparing the fish communities of RTRs to those of adjacent natural habitats. Surveying fish habitats in turbid waters necessitates the use of methods that can quantify the abundance, biomass, and length of fishes irrespective of visibility. Using an imaging sonar (1.2. MHz) and implementing a novel, pixel-based approach analogous to echo-integration, this study estimated the relative biomass density and length distribution of fishes at seven toppled oil and gas platform jackets in a Reefed Jacket Zone (RJZ) in the nearshore western Gulf of Thailand in comparison with a nearby coral reef. Biomass density was comparable at each habitat, despite extreme variability across the RJZ, attributed to the spatiotemporal stochasticity of larger, schooling fishes. However, fishes were larger at the RJZ, a trend supported by simultaneous stereo-video footage. The relative benefits and drawbacks of imaging sonar encountered in this study are also described.

1. Introduction

The offshore expansion of the oil and gas industry in the mid-twentieth century resulted in the installation of thousands of oil and gas platform jackets (the latticed steel structures that enclose drilling apparatus) and associated structures (hereafter collectively termed 'platforms') in the ocean (Parente et al., 2006). In tropical and sub-tropical latitudes, platforms can often attract a high level of biodiversity from nearby natural habitats (Jagerroos and Krause, 2016), including coral reefs (Fisher et al., 2015; Parravicini et al., 2013). This is enabled by the provision of hard substrate on homogeneous seabed where it was otherwise absent, for example in West Africa (Friedlander et al., 2014), the Gulf of Mexico (Ajemian et al., 2015a), northwest Australia (McLean et al., 2019; Pradella et al., 2014), and the Gulf of Thailand (Harvey et al., 2021; Alexander et al., 2022). Diverse benthic communities often develop on platforms, providing biogenic structural complexity that further augments the fish habitat value of platforms (Kolian and Sammarco, 2019; Sammarco et al., 2014). Over several decades, the biodiversity of platforms can begin to approximate natural habitats, transforming platforms into rich artificial reefs (Fortune and Paterson, 2020; Friedlander et al., 2014; McLean et al., 2019; Thomson et al., 2018).

* Corresponding author. School of Biological Sciences, King's College, University of Aberdeen, Aberdeen, United Kingdom.
E-mail address: e.sibley.20@abdn.ac.uk (E.C.P. Sibley).

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When a platform nears the end of its operational life, it is marked for decommissioning. In many jurisdictions, decommissioning has involved the complete removal of the infrastructure used for oil and gas production for onshore scrapping (Bull and Love, 2019). However, the anthropogenic decline of many marine ecosystems has placed a growing emphasis on preserving the biodiversity associated with platforms that would otherwise be displaced or destroyed if the platform was scrapped (Bull and Love, 2019; Fowler et al., 2018). Increasingly, platforms are being repurposed as dedicated artificial reefs, a process commonly termed Rigs-To-Reefs (RTR). The RTR process attempts to both retain the taxa associated with the platform and enhance local biodiversity by providing supplementary artificial habitat (Macreadie et al., 2011; Schulze et al., 2020). RTR projects can also be implemented to bolster both recreational and commercial fisheries, with notable examples in the Gulf of Mexico (Kaiser et al., 2020).

The RTR process generally comprises one of three processes: retaining the platform *in situ*, cutting the platform into two or more smaller structures that can then be arranged into a new reefscape, or toppling the platform onto its side (Fowler et al., 2014). Cutting and toppling obsolete platforms are often the favoured approaches when creating RTRs nearshore, to maintain water clearance above the structure for vessel navigation. For example, in the western Gulf of Thailand (GoT), seven platforms from an offshore location were towed approximately 150 km to nearshore and toppled in 2020 to create a Reefed Jacket Zone (RJZ) off the island of Koh Pha Ngan (Fig. 1, Marnane et al., 2022). The western GoT comprises many island-fringing coral reefs, but there is a paucity of complex habitat in deeper water (Harvey et al., 2021). Moreover, fish abundance and diversity in the GoT have declined after decades of intense fishing pressure (Satumanatpan and Pollnac, 2020). This has been compounded by various drivers of coral reef degradation (Hoegh-Guldberg et al., 2017; Hughes et al., 2003), including a severe bleaching event in 2010 (Hoeksema and Matthews, 2011).

Soft sediment is the prevailing substrate type in the GoT. On nearshore reefs, episodes of sediment disturbance from upwelling and strong currents can generate high turbidity. Under these circumstances, the detection and quantification of reef fishes using optical instruments (e.g., cameras) can be very challenging given the variability in visibility between sites and over time, which can be a confounding factor in statistical analyses. This can be circumvented by using light-independent techniques. Imaging Sonars (ISs) are high-frequency acoustic devices that generate camera-like images of markedly higher resolution than the displays from conventional sonars operating at lower frequencies. Unlike optical instruments, ISs can detect targets in the water column when visibility is limiting, and have been used extensively to quantify fishes in turbid water (e.g., Artero et al., 2021; Egg et al., 2017; Griffin et al., 2020; Rose et al., 2005). The high resolution and portability of ISs (typically achieved through integration into remotely operated vehicles, ROVs) also make them useful for surveying marine life around complex habitats, including natural reefs (Artero et al., 2021; Griffin et al., 2020) and artificial structures (Able et al., 2013; Plumlee et al., 2020; Sibley et al., 2023a, b; Van Hal et al., 2017). Although ISs typically cannot identify discrete species, they have been demonstrated to outperform optical cameras in the detection and enumeration of fish density (Egg et al., 2018; Sibley et al., 2023a).

Empirical evidence of the ecological benefit of RTRs can inform decisions regarding offshore platform decommissioning alternatives. Studies have demonstrated both fish biomass (Boswell et al., 2010) and density (Bollinger and Kline, 2017; Wilson et al., 2003) to be higher on RTRs than nearby natural reefs. However, the species richness and community heterogeneity of natural reefs are typically greater than RTRs, reflecting the greater habitat complexity and significantly more advanced successional state of natural reefs with a more diverse reef-associated fish assemblage (Streich et al., 2017; Wilson et al., 2003). The habitat value of RTRs relative to natural reefs is likely contingent on the RTR process used. For example, toppling platforms generally reduces the vertical relief of the structure, instead providing extensive horizontal relief in comparison to retained or cut platforms. This can limit the establishment of fish species that favour shallower depths, often in association with phototrophic benthic taxa (Harvey et al., 2021; Kolian and Sammarco, 2019). However, studies of fish assemblages on standing platforms prior to decommissioning to predict the value of retaining structures are more common than post-decommissioning assessments that actually test these predictions. For the GoT, quantifying the fish assemblages around RTRs in comparison with adjacent natural reef habitat will inform the effectiveness and long-term suitability of RTR decommissioning in the region, which can potentially contribute to the conservation and restoration of local reef-associated fish populations. This study used IS and a novel, pixel-based method to compare the biomass density and length distribution of fishes at the RJZ and a nearby coral reef off Koh Pha Ngan in the western GoT. The principal objective of the study was to ascertain the fish habitat value of the RJZ relative to the coral reef by quantifying differences in these two variables. This study also aimed to supplement a limited but growing body of research on IS application for quantifying coral reef fish taxa (e.g., McCauley et al., 2016, 2014).

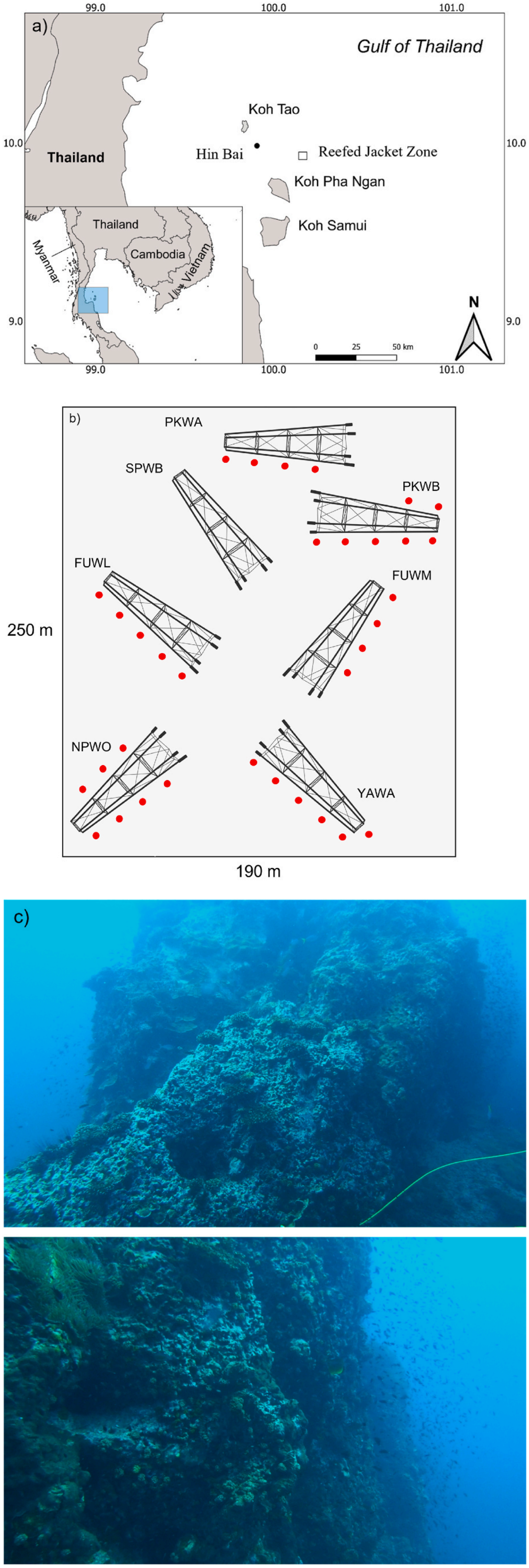
2. Methods

2.1. Study sites

The Reefed Jacket Zone (RJZ) north of Koh Pha Ngan comprises seven platforms (YAWA, PKWA, PKWB, SPWB, NPWO, FUWL, and FUWM) that were towed nearshore and placed horizontally on the seafloor between 2nd August and September 24, 2020, having been previously operating in the offshore GoT (Fig. 1a). The platforms were deployed within an approved reefing zone covering an area of approximately 250 m × 190 m, and range in depth from 25 to 30 m as measured from the top of the platforms. The arrangement of the platforms is depicted in Fig. 1b.The platforms are all 70 m long, and rise approximately 2 and 4.5 m from the seabed at the apex and base, respectively. The total habitat area of the platforms is approximately 9000 m^2. The RJZ lies approximately 20 km southeast of Hin Bai (also known as "Sail Rock"), a pinnacular coral reef situated between Koh Pha Ngan and Koh Tao. The reef pinnacle is 20 m tall, on a slope that extends to 40 m deep (Fig. 1a, c), encompassing an area of approximately 1300 m^2. Hin Bai is a popular dive site because of its complex architecture and high reef fish diversity, ranging from small reef-attached taxa to large benthopelagic fishes and, occasionally, charismatic megafauna (e.g., whale sharks). Nonetheless, Hin Bai is subjected to regular fishing pressure, particularly in the diving off-season between October and December. Carangid and Lutjanid species are the typical fisheries targets in the region (Pauly and Chuenpagdee, 2003). Discarded fishing gear was seen entangled on portions of the platforms, reflecting the intense fishing pressure in the wider western GoT. Profuse soft coral and algal growth covers many of the platform crossbeams, in contrast with a higher scleractinian coral cover at Hin Bai, including branching *Acropora* colonies and *Porites* boulder corals.

2.2. Instruments

Imaging Sonar (IS) footage was collected from Hin Bai and the RJZ using two Blueprint Subsea Oculus M1200d multibeam ISs (www.blueprintsubsea.com/oculus/), both operating at 1.2 MHz. Higher frequencies afford greater resolution, but at the expense of range. This frequency was chosen to allow for the detection of fishes with sufficiently high resolution to permit counting and sizing, whilst providing adequate range (up to 40 m) to facilitate safe navigation at both habitats. One IS was mounted on an Oceanbotics SRV-8 ROV (www.oceanbotics.com/srv-8/), and the other on a BlueRobotics Blue2 ROV (www.bluerobotics.com/store/rov/bluerov2/). Both ROVs were tethered to the surface via an umbilical. The location of each ROV was determined using a



(caption on next column)

Fig. 1. Depictions of a) the location of the two study sites: the coral reef Hin Bai, and the Reefed Jacket Zone (RJZ) comprised of seven toppled oil and gas platforms, both located off Koh Pha Ngan in the Gulf of Thailand. The location of the study sites relative to southeast Asia is represented by the blue square in the inset map; b) the arrangement of the platforms in the RJZ. The approximate locations of the sampling stations at each platform are indicated in red. The imaging sonar was operated at 7–10 m from the platforms for all sampling stations, with stations separated by at least 20 m. SPWB could not be surveyed due to an instrumental fault; and c) the pinnacular profile of Hin Bai from both front-on and side-on perspectives, taken from stereo-video footage collected on the south side of the reef. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Seatrac *X*150 Ultra-Short Baseline (USBL) Beacon on the boat and an *X*010 Modem Beacon attached to each ROV, facilitating navigation and enabling calculations of distance travelled. Each ROV also housed an altimeter to record depth, and an onboard 1080p optical camera. Stereo-video cameras were also mounted to each ROV for sampling the species composition, abundance, length, and biomass of fish assemblages as part of a conjunctive, longer-term study (E. S. Harvey et al., *pers. comm.*; see Schramm et al., 2021 for description of stereo-video methodology).

Visibility at the RJZ, ascertained using the onboard stereo-video system, was consistently measured at less than 3 m, and ranged from around 8 to 15 m at Hin Bai. These visibilities are broadly consistent at both habitats year-round (Se Songploy *pers. comm*). Both habitats were surveyed between the 15th and 16th of August, 2022, during daylight hours.

2.3. Data acquisition and processing

At Hin Bai, the ROVs were piloted around the reef at a depth of 6–22 m. At 20 m horizontal intervals (hereafter termed "sampling stations"), the ROVs were oriented to face the reef at a distance of 7–10 m (facilitated by the distance gradings on the Oculus Viewpoint display; www.blueprintsubsea.com/oculus/support.php), and held stationary for 10 s at a level pitch and roll to maintain consistent viewing angles, generating 10 s of continuous IS footage at each sampling station. This process was repeated at the RJZ for six of the seven platforms (excluding SPWB, which was not surveyed due to an instrumental fault) at depths of 25–28 m. PKWA, FUWM, and NPWO were surveyed using the SRV-8, and PKWB, YAWA, and FUWL surveyed using the Blue2. Overall, 25 sampling stations were achieved at the coral reef, and 38 at the RJZ. The arrangement of sampling stations at each platform in the RJZ is displayed in Fig. 1b.

From the 10-s footage at each sampling station, one still frame was extracted at 5 s. To ensure no overlap in sampling volume between each sampling station, the frames were cropped to only include the middle 65° of the IS display (Fig. 2 Step 1). At short ranges, the IS beam array is not fully formed, hence objects in the immediate vicinity of the sonar (termed the "Near-Field Zone, NFZ") are not completely ensonified (Han and Uye, 2009). From each frame, an NFZ of 2 m was subtracted (Step 2) that corresponded with a high incidence of "speckle noise" in the NFZ at both habitats, likely due to the ensonification of suspended sediment that could not be discriminated from fishes within 2 m range. Individual frames were used to count fishes as opposed to continuous footage to mitigate the risk of multipassing, whereby the same fishes exit and re-enter the Field-Of-View (FOV) of the IS and are counted multiple times. Multipassing can cause overestimations of fish abundance and is especially apparent for fishes that mill in the FOV (Eggleston et al., 2020; Grote et al., 2014; Magowan et al., 2012; Petreman et al., 2014; Viehman and Zydlewski, 2015). Quantification of fishes in individual frames is analogous to MaxN calculations to mitigate overestimations of fishes on optical cameras (Schobernd et al., 2014). However, repeat counting may have occurred for fishes that followed the ROV between sampling stations, although no conspicuous instances of following were observed on either the IS or stereo-video, nor marked changes in fish

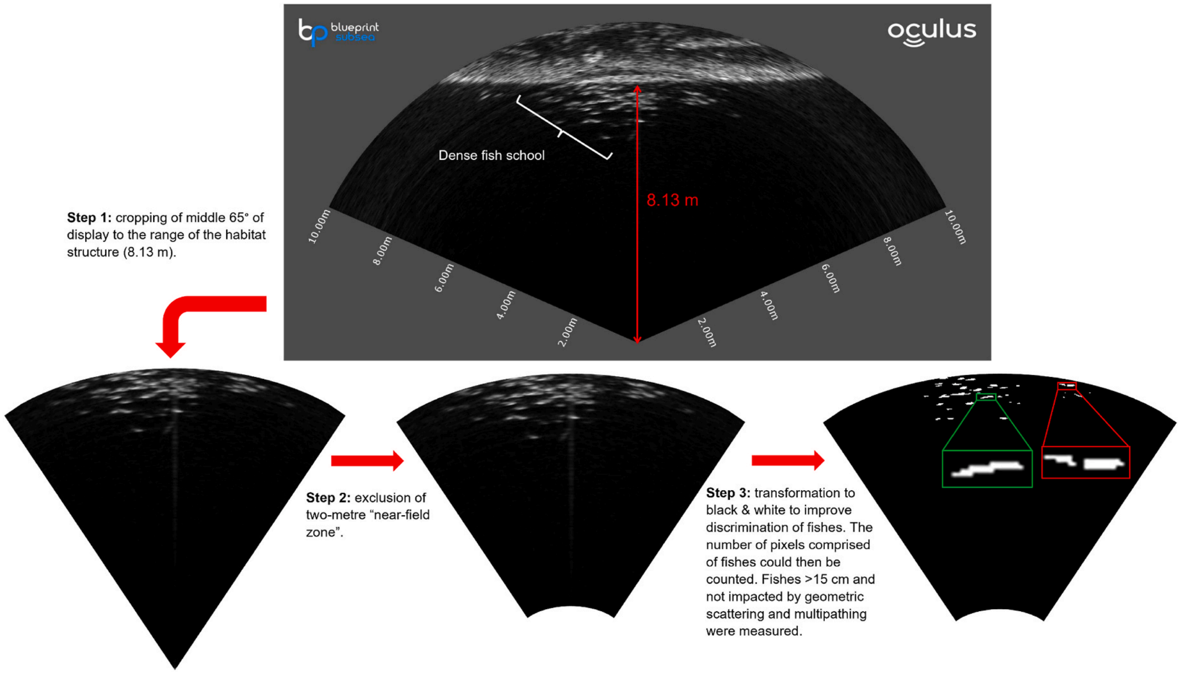


Fig. 2. The processing workflow of imaging sonar still frames from sampling stations at the coral reef Hin Bai and Reefed Jacket Zone (RJZ), exemplified using a still frame from a sampling station at the platform PKWA. Three steps were implemented to calculate the biomass density and length of fishes in each frame. **Step 1** exclusion of the physical structure of the habitat from the sampling volume by cropping the display to the range of the nearest point of the habitat structure from the sonar. The frame was also truncated to only include the middle 65° of the display to ensure no overlap in sampling volume with adjacent sampling stations. **Step 2** exclusion of the "Near-Field Zone" (NFZ; estimated at 2 m range) in which targets are often only partially ensonified. This also excluded any "speckle noise" in the NFZs caused by the ensonification of suspended sediment. **Step 3** transformation of the frame to black and white, necessary to quantify schooling fishes, which comprised the majority of fishes detected at both Hin Bai and the RJZ. These fishes could not be consistently discriminated from each other on the original sonar display. Instead, the number of pixels comprised of fishes could then be counted and converted to density using the known sampling volume of each frame. The lengths of fishes on the transformed frames were also measured. Fishes subjected to geometric scattering or multipathing that often appeared as segmented targets with abrupt start and/or end points (as apparent for the target on the right in the red rectangle) were not measured. The limited resolution of the imaging sonar and high density of fishes meant that true fishes smaller than 15 cm could not be consistently discriminated from segmented targets. Instead, only fishes larger than 15 cm were measured, provided they were approximately ellipsoid in shape with a definitive start and end point (e.g., the target in the green rectangle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

abundance at each sampling station within the 10-s sampling intervals. This study acknowledges potential non-independence of the still frames within each habitat, notwithstanding high species-specific variability in responses to underwater vehicles that may be further influenced by differences in visual reception at each habitat (Lorance and Trenkel, 2006; Stoner et al., 2008).

Preliminary inspection of the IS footage revealed that fishes at both habitats were near-exclusively schooling, defined as swimming in the same direction as, behaving similarly to, and of comparable size to more than two other fishes (Sibley et al., 2023c). Moreover, schooling fishes were often densely aggregated (Fig. 2), whereby individual fishes were consistently estimated to be less than one-quarter of their body length away from the nearest other fish in the school, as determined on the IS display. These densely aggregated fishes could not be consistently discriminated from each other, preventing counts of individual fishes. Counts of individuals were also challenged by instances of geometric scattering and multipathing, whereby echoes from fish body parts of varying density (geometric scattering), or reverberation of echoes from solid background objects (such as the physical habitat structure) before being received by the IS (multipathing), can cause fishes to appear as more than one discrete target (Faulkner and Maxwell, 2020; Foote, 1980; Sibley et al., 2023a; Simmonds and MacLennan, 2005).

To improve the resolution of the IS frames to help discriminate densely aggregated fishes, frames were converted to black and white in Microsoft PowerPoint (Fig. 2 Step 3). The black and white frames were then imported to GIMP (v2.10.32; -www.gimp.org/downloads/) in order to count the number of pixels comprised of fishes (hereafter termed 'fish pixels'). This process is analogous to echo-integration for split-beam echosounders that sum the energy of all echoes returned at a discrete intensity threshold, ascribed to fish targets to proxy fish biomass density (Scoulding et al., 2015; Simmonds and MacLennan, 2005). Fish pixels of a luminance of 100 or greater on a black-to-white scale of 0–255 were counted, as this threshold consistently eliminated residual non-fish echoes whilst preserving true fish targets. The clarity of fishes was also not impacted by occasions of intense speckle noise in the near-field that may have reduced the clarity of targets at range in non-transformed sonar imagery. Based on the degree of noise from suspended sediment and other non-fish targets, future studies may look to implement a different luminance threshold, such that the number of fish pixels in this study must be considered as relative. Systematic calibration methods would standardise the quantification of fish echoes using different IS models and frequencies, thus clarifying the relationship between luminance and target strength, but these are yet to be developed (Martignac et al., 2015; Sibley et al., 2023b). The number of fish pixels was then converted to density by dividing the number of pixels by the sampling volume of the IS at each sampling station. Sampling volume was calculated after Sibley et al. (2023a) using the formula:

$$V_a = \frac{2}{3} \times \beta \times r^3 \times \sin\left(\frac{\alpha}{2}\right) \qquad \text{Equation 1}$$

where: β = vertical aperture of 20° expressed in radians (0.349); r = distance from the sonar face to the nearest point of the structure; and α = horizontal aperture of 65° (1.134 radians). From this, the volume of the excluded NFZ of 2 m range (1.00 m^3) was subtracted.

The black and white IS frames were then exported to ImageJ (v1.54 b; www.imagej.net/ij) to measure the length of fishes in each frame. The ImageJ measurement tool was calibrated by counting the number of pixels across the known range (*r*) of the IS display, thus determining the size of individual pixels in each frame. Only discrete 'fish-like' targets (roughly ellipsoid in shape with definitive start and end points that tapered from the middle of the target) were measured to exclude targets generated by geometric scattering and multipathing that typically appeared segmented with abrupt start and/or end points (Fig. 2 Step 3). The resolution of the IS meant discrimination of true fishes from instances of geometric scattering and multipathing was particularly challenging for targets smaller than 15 cm. Therefore, only fish-like targets larger than 15 cm were measured. The data processor (E.C.P. Sibley) has several years experience identifying and mitigating for instances of geometric scattering and multipathing, such that measurements of 'true' fish targets in this study are considered accurate and robust. However, the transformation and measurement of fishes at the chosen luminance threshold, coupled with the myriad causes of error in length measurements of targets ensonified by IS (Sibley et al., 2023b), means length measurements in this study must be considered as relative. In total, 1163 fishes were measured at Hin Bai, and 535 at the RJZ (total $n = 1698$).

Stereo-video imagery was used to calculate fish lengths concurrently to those acquired using IS when visibility was adequate to visualise and measure fishes. Stereo-video lengths were estimated in SeaGIS EventMeasure (www.seagis.com.au/event.html) using continuous footage collected at Hin Bai and across the entire RJZ, predominantly when moving the ROVs between sampling stations, and were included for comparison to the IS imagery as an independent means of quantifying fish lengths. Unlike IS, stereo-video measurements were not constrained by a minimum measurable length, thus providing estimates of fishes smaller than 15 cm. In total, 3603 fishes were measured at Hin Bai (of which 643 fishes were ≥15 cm) and 897 at the RJZ (684 fishes were ≥15 cm), reflecting the greater visibility at Hin Bai that permitted the detection and measurement of fishes at greater ranges.

2.4. Data analyses

The number of fish pixels quantified at each sampling station complex was modelled against habitat type – the coral reef Hin Bai or RJZ – in a Generalised Linear Mixed-Effects Model. The model assumed a negative binomial distribution (to accommodate overdispersion in the number of fish pixels across habitat types) with a log-link (the canonical link function for negative binomial Generalised Linear Models s on the same scale as the model offset – see below). The data were highly variable in the number of fish pixels between the six platforms surveyed at the RJZ (Fig. 3). To account for this variability, an intercept-only random effect of platforms (YAWA, PKWA, PKWB, SPWB, NPWO, FUWL, or FUWM) was included. To account for differences in the range of the imaging sonar from the habitat structure (and, hence, the sampling volume of the imaging sonar) at each sampling station, the natural logarithm of sampling volume was specified as an offset in order to treat the dependent variable as density (i.e., the number of fish pixels per unit volume, or 'pixel biomass density').

IS fish lengths were modelled as a Linear Mixed Effects Model to determine differences between Hin Bai and the RJZ. Again, an intercept-only random effect of platform was included in the model to account for variability in fish lengths between individual platforms in the RJZ, although this appeared smaller than for pixel biomass density (Fig. 4). Stereo-video fish lengths (filtered to only include fishes ≥15 cm) compared between Hin Bai and the entire RJZ were modelled as a Generalised Linear Model, assuming a gamma family with a log-link due to the positive skew in lengths at both habitats. Differences in length distributions between habitats as quantified by both IS and stereo-video were also assessed using asymptotic Kolmogorov-Smirnov tests.

All the models were constructed in R (V4.3.1; R Core Team, 2013). The pixel biomass density model was formulated using the 'glmer.nb' function in the package 'lme 4' (eBates et al., 2015), with suitability of model fit checked using diagnostic plots in the DHARMa package (Hartig, 2020). The significance of the effect of habitat type on pixel biomass density was determined using a Wald Z-test. The IS fish length model was formulated using the 'lmer' function in the package 'lmerTest' (Kuznetsova et al., 2017) using Restricted Maximum Likelihood (REML). Parameter-specific p-values were derived using the '*t*-as-*z*' approach of normal approximation described in Luke (2017). The stereo-video fish length model was formulated using the 'glm' function in the package 'stats' (R Core Team, 2013), with significance determined using Analysis of Deviance. Statistical significance for all analyses was determined at the threshold of $p < 0.05$.

3. Results

Mean pixel biomass density was over two-and-a-half times greater at Hin Bai (48.3 pixels m^{-3}) than at the RJZ (18.3 pixels m^{-3}), with density

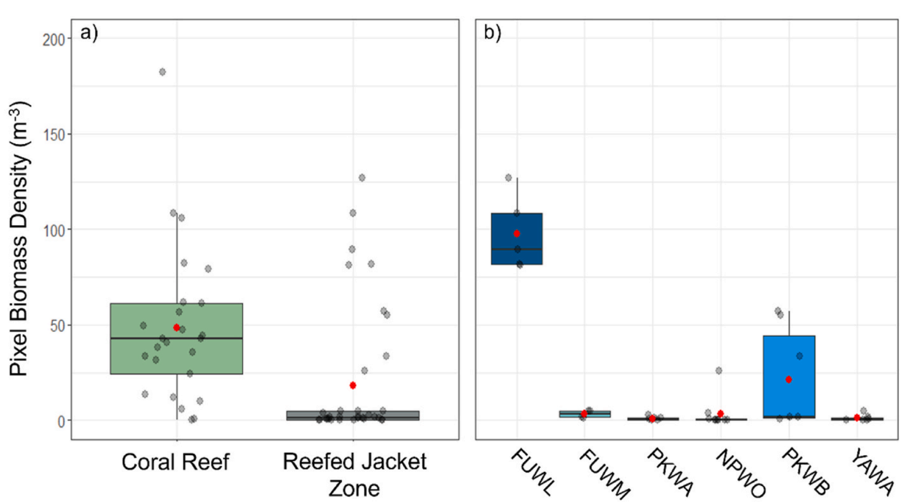


Fig. 3. The distribution of pixel biomass density at a) the coral reef Hin Bai and the Reefed Jacket Zone (RJZ), and b) at the six platforms comprising the RJZ, as detected using a 1.2 MHz Blueprint Subsea Oculus Imaging Sonar. Mean pixel biomass density at each habitat is denoted by the red circles. The black lines within each box denote the median. The whiskers represent values outside the interquartile range (contained within the box). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

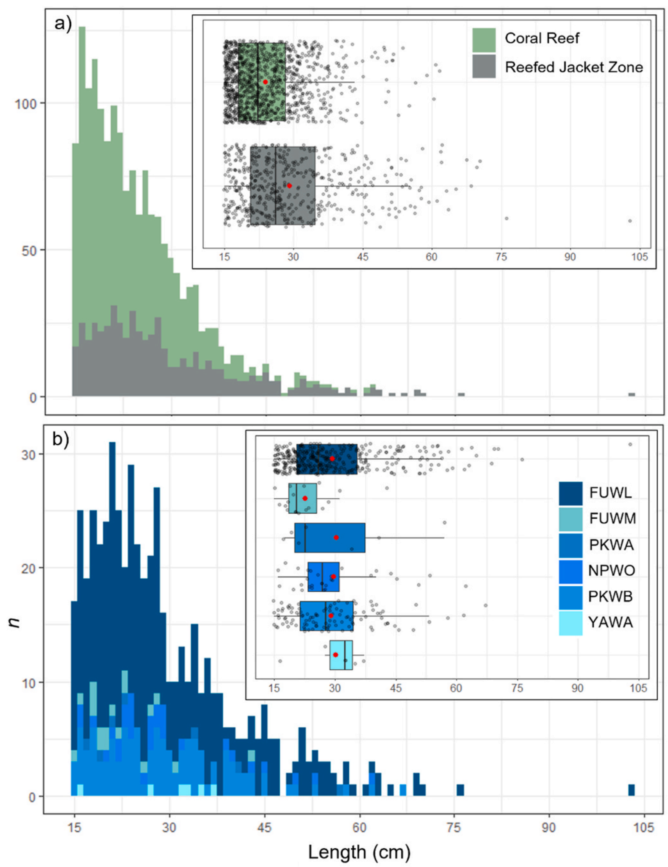


Fig. 4. Distributions of the lengths of fishes ≥15 cm (the minimum size at which fishes could be consistently discriminated from instances of geometric scattering) estimated using IS at a) the coral reef Hin Bai and the entire Reefed Jacket Zone (RJZ), and b) at each of the six platforms comprising the RJZ. Only fish targets that did not exhibit geometric scattering or multipathing were measured. Embedded are boxplots displaying the mean fish length (red circle), median fish length (black bar), and fish lengths beyond the interquartile range (whiskers) at each platform. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

at four of the platforms (FUWM, NPWO, PKWA, and YAWA) ranging from just 0.91 to 3.34 pixels m^{-3} (Fig. 3). Despite this, pixel biomass density was not significantly lower at the RJZ overall (Est. = −2.160 ± 1.510 Standard Error, Z = −1.430, p = 0.152). Visual inspection of pixel biomass density from each platform suggested that this was attributable to markedly higher densities at FUWL than the remaining five platforms. Moreover, mean pixel biomass density at FUWL (97.5 m^{-3}) was more than twice that at Hin Bai; four-and-a-half times greater than at the next densest platform, PKWB (21.4 m^{-3}); and over two orders of magnitude greater than NPWO, the platform with the lowest mean density (0.910 m^{-3}). Pixel biomass density varied markedly at Hin Bai, from zero to 182.3 pixels m^{-3}. However, the sample sizes achieved at each platform were too small to permit robust statistical analysis to determine differences in pixel biomass density and IS fish lengths between platforms.

Relative to pixel biomass density, mean fish length as quantified using IS was consistent across platforms, despite notable variability at FUWL, NPWO, PKWA, and PKWB, and a greater variability overall than at Hin Bai (Fig. 4). Across the RJZ, mean length ranged from 22.7 cm at FUWM to 30.2 cm at YAWA. Fishes at the RJZ were approximately 5 cm larger on average (29.2 ± 0.518 cm) than fishes at Hin Bai (23.9 ± 0.224 cm), with analysis of the Linear Mixed Effects Model revealing this difference to be significant (Est. = 4.794 ± 1.694, t = 2.830, p < 0.01; Fig. 4). Differences in length distribution between Hin Bai and the RJZ were supported by the Kolmogorov-Smirnov test (D = 0.188, p < 0.001). Of all the platforms, only FUWM had a lower mean fish length than Hin Bai (23.9 cm). Of the 10 largest fishes recorded in this study, 9 were detected at FUWL, including the largest fish measuring 103.0 cm. The largest fish detected at Hin Bai measured 61.7 cm. Comparatively few measurable fishes at YAWA (n = 6) and NPWO (n = 7) made analysis of differences in fish length between platforms unviable, limiting comparisons to Hin Bai and the RJZ. No marked variation in the range of fishes in the IS FOV was observed at either habitat, including at higher fish densities.

The differences in fish lengths as determined using IS between the two habitats contrasted with the length estimates made using concurrent stereo-video. Analysis of deviance revealed no significant difference in the length of fishes ≥15 cm between Hin Bai and the RJZ (Est. = 0.02 ± 0.022, t = 0.913, p = 0.361; Fig. 5). On average, fishes at the RJZ (28.7 ± 0.369 cm) were only 0.6 cm smaller than fishes at Hin Bai (29.3 ± 0.538). In contrast, a Kolmogorov-Smirnov test reported a significant difference between the stereo-video length distributions of fishes ≥15 cm at Hin Bai and the RJZ (D = 0.174, p < 0.001), indicating that fish lengths at Hin Bai were higher than at the RJZ. However, when incorporating fishes of all measurable length, only 17.8% of fishes were ≥15 cm at Hin Bai, compared to 76.2% at the RJZ.

The largest fish measured using stereo-video was 112.2 cm long, detected at Hin Bai. Stereo-video footage also provided information on species identification, which was not possible using IS, revealing that the RJZ was dominated by schools of larger fishes, including bigeye trevally (*Caranx sexfasciatus*) and Java rabbitfish (*Siganus javus*). In contrast, Hin Bai was characterised by a high abundance of smaller taxa, including damselfishes (*Neopomacentrus* spp.) and redbelly yellowtail fusilier (*Caesio cuning*).

4. Discussion

This study quantified the biomass density and length distribution of fishes associated with several toppled oil and gas platform jackets in a Reefed Jacket Zone (RJZ) in the western Gulf of Thailand and a nearby coral reef. A complete understanding of fish habitat value at Hin Bai and the RJZ would necessitate more dedicated quantification of species diversity, which was not possible here due to the limited capacity of IS to discriminate species and poor visibility that constrained species detection using stereo-video. However, the habitat value of the RJZ in terms of fish biomass density and length distribution (which particularly inform fisheries value) was considered to be at least comparable to an

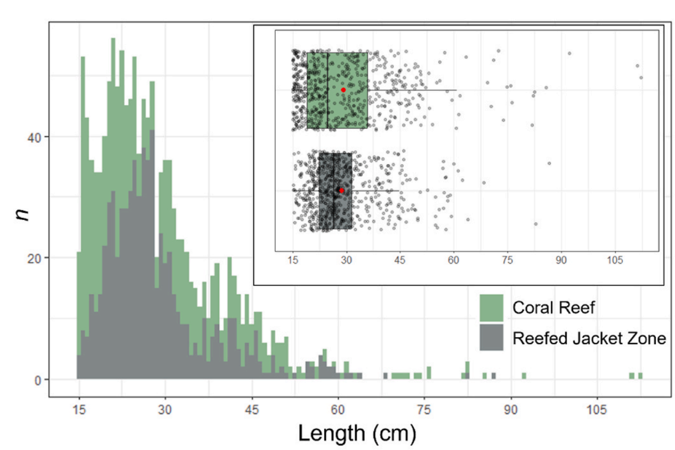


Fig. 5. Distribution of stereo-video fish lengths (filtered to only include fishes ≥15 cm for comparability to IS measurements) at the coral reef Hin Bai and the Reefed Jacket Zone, including a boxplot displaying the mean fish length (red circle), median fish length (black bar), and fish lengths beyond the interquartile range (whiskers) at each habitat. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

adjacent natural habitat, notwithstanding incongruence between IS and stereo-video length distributions. Such assessments are essential in justifying future decommissioning projects that convert oil platforms into dedicated artificial reefs. This reflects a growing emphasis on environmentally conscious decommissioning, especially in the tropical ocean, where biodiverse faunal assemblages often aggregate around oil and gas infrastructure (Fortune and Paterson, 2020; Friedlander et al., 2014; McLean et al., 2019; Thomson et al., 2018).

4.1. Pixel biomass density and fish length distribution

Pixel biomass density at the RJZ was similar to density at the pinnacular coral reef Hin Bai, notwithstanding substantial variability across the platforms. Differences in fish length between Hin Bai and the RJZ were less clearly resolved. IS estimated fishes to be larger at the RJZ, though stereo-video measurements did not corroborate this trend. Overall, in terms of pixel biomass density and fish length, this study demonstrates similarities between the fish communities at each habitat, despite the RJZ being installed two years before this study. Notably, larger fishes at the RJZ as quantified using IS indicates an abundance of potential fisheries targets that may benefit local populations.

Differences in the fish assemblages at Hin Bai and the RJZ are likely underpinned by the contrasting depth and physical profiles of each habitat. Both habitats are situated on homogeneous soft sediment that is limited in physical habitat structure (Harvey et al., 2021). Despite encompassing a smaller area than the RJZ, the pinnacle configuration of Hin Bai affords high vertical relief, in contrast to the limited vertical profile (~2–3 m) of the platforms. Instead, toppled RTRs provide extensive fish habitat in the horizontal dimension. Vertical stratification is a conspicuous element of fish ecology on both natural and artificial reefs (Ajemian et al., 2015b; Brokovich et al., 2008; McLean et al., 2019; Thomson et al., 2018; Torquato et al., 2017). Smaller, reef-attached fishes are typically confined to shallower depth strata (Smallhorn-West et al., 2017), often following the zonation of depth-limited benthic organisms (e.g., phototrophic corals) that provide food and refuge (Harvey et al., 2021; Kahng et al., 2010; Kolian and Sammarco, 2019). Larger piscivorous fishes typically characterise deeper reef strata (Ayalon et al., 2010; Kahng et al., 2010; Scott et al., 2022), further confining smaller fishes to shallower depths where the risk of predation is lower. These habitat associations are further impacted by visibility. Greater visual fields underpin reduced predation of smaller reef fishes (Rilov et al., 2007), such that vulnerable taxa may stay in closer proximity to physical habitat structure for refuge purposes in waters of poor visibility (e.g., at the RJZ), whilst exhibiting greater vigilance to possible attacks (Hess et al., 2019). The absence of shallow water habitat, abundance of potential predators, and unfavourable abiotic conditions have likely inhibited the establishment of greater numbers of smaller fishes at the RJZ (Ajemian et al., 2015a). Benthic growth on the platforms (as visualised using the stereo-video cameras) was sparser and less structurally complex than at Hin Bai, dominated by algae and soft coral. In contrast, the relatively high scleractinian coral cover at Hin Bai, characteristic of more successionally-advanced and healthy reefs (Diaz-Pulido et al., 2009; Doropoulos et al., 2017; Sammarco et al., 2014; Sweatman et al., 2011), affords robust and heterogeneous physical habitat at size scales relevant to smaller fishes that are more vulnerable to predation (Coker et al., 2014; Geange, 2010; Rogers et al., 2018) and adverse environmental conditions (Johansen et al., 2007, 2008) than larger fishes. The conversion of standing platforms to RTRs frequently alters the abundant and complex benthic growth that can develop on the structure, temporarily reducing the habitat quality for reef-attached fishes and often requiring several decades to recover (Kolian and Sammarco, 2019; Bull and Love, 2019). Poor visibility aside, the abundance of small, reef-attached fishes at the RJZ may therefore be expected to increase over time as a more diverse and complex benthic community develops on the platforms (see Burt et al., 2011; Scarborough Bull and Kendall, 1994). Typically, the configuration and complexity of platforms differ from natural reefs, creating structurally unique and novel habitats (Van Elden et al., 2019).

The scale of the artificial structural complexity provided by the RJZ (e.g., platform crossbeams) far exceeds the length distribution of most reef-attached fishes. For example, the overhead refuge afforded by platform crossbeams is often too large to adequately shelter smaller fish taxa (see Hixon and Beets, 1993). Instead, the provision of artificial habitat in deeper water appears to support high densities of larger fishes (Boswell et al., 2010). This was evidenced in an assessment of the fish communities associated with the platforms when standing in the offshore GoT, prior to formation of the RJZ. Community biomass at the standing platforms was dominated by Carangids (particularly bigeye trevally, *Caranx sexfasciatus*) and Caesionids (Harvey et al., 2021). Moreover, deeper strata, typically 40–55 m, contained a higher fish biomass and lower abundances of smaller species than shallower zones. Natural reefs of equivalent depth to the RJZ surveyed here may accommodate similar assemblages with comparable vertical zonations to those reported in Harvey et al. (2021). However, such reefs are near-absent in the nearshore GoT, further emphasising the importance of RTRs in providing deep-water habitat for larger fishes that is naturally scarce (Macreadie et al., 2011).

This study observed marked differences in pixel biomass density across the RJZ. Notably, mean pixel biomass density at FUWL was more than double that at Hin Bai, and four-and-a-half times greater than at the next densest platform jacket (PKWB). This stochasticity may reflect the taxonomic composition of the surveyed fish assemblage. Opportunistic footage collected from the stereo-video cameras (when at sufficiently close range to permit observation, despite the poor visibility) revealing a relatively high occurrence of Carangids, which appeared as relatively large (>30 cm) and near-exclusively schooling fishes on the IS. For example, at FUWL, a school of around a hundred *C. sexfasciatus* was observed on the stereo-video cameras near the top of the platform. *C. sexfasciatus* is a large, schooling, benthopelagic piscivore that is known to aggregate around artificial reefs in the GoT (Harvey et al., 2021; Madgett et al., 2022). Several previous studies have reported fish assemblages at platforms to be dominated by large benthopelagic taxa, most commonly Carangids and Lutjanids (Ajemian et al., 2015b; Bolser et al., 2021; Friedlander et al., 2014; Harvey et al., 2021; Torquato et al., 2017; Wilson et al., 2003) that aggregate around artificial structure for reproductive purposes (Madgett et al., 2022), or in pursuit of aggregated small fish prey (Streich et al., 2017). The patchy distribution, social tendencies, and roving behaviours of these taxa have previously underpinned high spatiotemporal variation in fish density and biomass at platforms (Bolser et al., 2021; Stanley and Wilson, 2004; Wilson and Nieland, 2004), likely mirroring the stochastic distribution of prey taxa that use platforms for refuge (Barker and Cowan, 2018; Bolser et al., 2020) or foraging (Egerton et al., 2021). Variable current regimes around high-complexity habitats can also underpin the formation and distribution of fish schools in response to the accumulation of current-vectored prey (Genin, 2004). Future quantification of current speed and direction at each platform jacket may explain a significant proportion of the variability observed here. Broadly, this study evidences strong variation in fish community abundance and, by possible extension, productivity across artificial structures, even in the same ecological setting (Fowler et al., 2015b). Acknowledging the relatively short survey period in this study, this variation will likely be elucidated over longer-term monitoring, specifically under consideration of the composition and behaviour of the local fish assemblage. Further surveillance of the RJZ fish assemblage, building on the methods and findings of this study, can help optimise the configuration and location of toppled platforms to reflect the dynamic spatio-temporal functionality and distribution of reef fish communities (Bollinger and Kline, 2017).

4.2. Imaging sonar application

The capacity of IS to provide camera-like footage of fish assemblages in turbid environments (e.g., Artero et al., 2021; Egg et al., 2017; Griffin et al., 2020; Rose et al., 2005) permitted the quantification of fishes in this study despite poor visibility at the RJZ. Application of the IS at 1.2 MHz afforded both adequate resolution and sampling volume to detect and measure fishes across both Hin Bai and the RJZ. At the RJZ, the fish length distributions quantified using IS were similar to those estimated using stereo-video, indicating the capacity of IS to detect trends in fish communities that have traditionally been investigated using optical instruments, albeit above a minimum measurable length of 15 cm. Stereo-video measurements alluded to larger fishes at Hin Bai than at the RJZ when excluding fishes smaller than 15 cm. These smaller fishes comprised over 76% of all fishes detected using stereo-video at Hin Bai. Nevertheless, resolving this discrepancy in length distributions between stereo-video and IS will optimise the conjunctive application of both methods in future studies, and should be a priority for future research that may ultimately aim to provide a systematic calibration of IS to standardise both quantification of biomass density and length distribution.

The high fish densities encountered in this study at both habitats (reflecting the near-exclusive schooling behaviours of detected fishes) prevented discriminating and counting individual fishes using IS at the implemented frequency. Instead, this study used a novel approach to quantifying biomass density by counting the number of pixels on a black-and-white-transformed display that corresponded to fishes, deduced using a discrete luminance threshold. Through this transformation, the length of fishes could also be estimated by quantifying the size of individual pixels on the IS display. Although range has previously been demonstrated to impact the accuracy of fish measurements using IS due to decreasing resolution at range, this has only been reported at ranges typically exceeding 10–20 m when operating between 1.1 and 1.8 MHz (Burwen et al., 2010; Daroux et al., 2019; Helminen et al., 2020). Nonetheless, studies that implement a pixel-based approach to measuring fishes with IS have considered underestimation of fish lengths at range as the number of pixels per unit length decreases with range (Able et al., 2013; Holmes et al., 2005). Likewise, pixel biomass density is contingent on the location of fishes in the IS FOV, with fishes at greater ranges comprising fewer pixels than fishes of equivalent length at closer ranges. The length measurements and densities of fishes in this study should be considered as relative between habitats and among structures, despite the comparatively short sampling ranges used, especially when considering the assorted drivers of erroneous IS length measurements (Sibley et al., 2023b). However, this study did not observe any systematic differences in the range of fishes at each sampling station, such that the pixel-based approach to quantifying length and biomass density is considered appropriate at the frequency (and, hence, ranges) applied.

Despite improving the discrimination of individual fishes using black-and-white transformation, smaller fishes (typically <15 cm) remained consistently challenging to distinguish and measure using IS, especially for dense schools that were likely comprised of Caesionids. Furthermore, fishes smaller than 15 cm were often indistinguishable from instances of geometric scattering and multipathing that further inhibited discrete counting (see Faulkner and Maxwell, 2020; Foote, 1980; Sibley et al., 2023a; Simmonds and MacLennan, 2005). Accordingly, smaller fishes, including reef-associated taxa common to tropical coral reefs (e.g., Pomacentrids, Chaetodontids), are likely underrepresented in the IS length data presented here. In contrast, stereo-video was capable of measuring fishes as small as 1.7 cm. Therefore, stereo-video can estimate the length distributions of fishes that are too small to be measured using IS, as well as providing alternative evidence as to the length distribution of fishes 15 cm or larger.

Some reef-associated taxa are challenging to detect (let alone measure) with IS. When the acoustic pulses propagated by IS intercept physical habitat structure and associated benthic growth, the resulting echoes can mask fishes in close proximity to these features, including fishes occupying interstitial spaces bordered by the habitat structure (Sibley et al., 2023a). On structurally-complex reefs, cryptic fishes occupying interstitial spaces can account for high proportions of total reef fish density and diversity (Willis, 2001). Ultimately, the majority of fishes quantified by both IS and stereo-video in this study were larger, more mobile species that occupied the waters around the physical habitat structure, in the so-called "field-of-influence" (Ajemian et al., 2015a; Boswell et al., 2010). To quantify smaller, reef-associated fishes for more comprehensive estimates of fish abundance at both artificial and natural reef habitats, future investigations may look to implement alternative sampling methods that are less susceptible to physical interferences, such as high-definition optics (under adequate visibility), or extractive techniques. These alternative methods can also provide the evidence needed to inform the taxonomy of fishes detected by IS (e.g., Faulkner and Maxwell, 2020; Kerschbaumer et al., 2020; Lankowicz et al., 2020; Rakowitz et al., 2012; Sibley et al., 2023a, b; Smith et al., 2021). These methods can attribute fishes of particular length detected by IS to particular species, a process that will ultimately inform both the fisheries value and species-specific length distributions of ensonified fish assemblages at different habitats. Ultimately, this study contributes to a growing body of literature on the capacity of IS to quantify fishes on tropical and subtropical artificial (e.g., Plumlee et al., 2020; Sibley et al., 2023a) and natural reefs (McCauley et al., 2014, 2016). Further such investigations will improve our understanding of the relative benefits and limitations of IS application in structurally complex and biodiverse habitats.

5. Conclusion

This study empirically demonstrates the fish community at reefed oil and gas platform jackets in the Gulf of Thailand (GoT) to be broadly comparable to an adjacent coral reef in terms of biomass density and fish length. These findings conform with studies from the Gulf of Mexico that evidence greater fish richness on Rigs-To-Reefs (RTRs) than adjacent natural reefs (Bollinger and Kline, 2017; Boswell et al., 2010; Wilson et al., 2003). Evaluating the benefits of different decommissioning strategies for fish assemblages requires a regional, case-by-case approach (Fowler et al., 2018). The results presented here are the first known comparative quantifications of fish assemblages on reefed platform jackets and natural reefs in the GoT, and may justify continued installations of artificial infrastructure in the region to the potential benefit of both biodiversity and fisheries. Notably, this study also demonstrates the complementarity of IS and stereo-video, and further integration of these two methods will undoubtedly provide more complete assessments of fish communities in habitats of varying complexity and visibility.

Further insights into the ecology of RTRs will more accurately resolve the long-term suitability of retaining oil and gas infrastructure in the ocean. The aggregation of key fisheries taxa around RTRs, including the Carangids detected here, theoretically benefit local human populations. However, intense fishing pressure could subvert the ecological benefits of RTRs (Jagerroos and Krause, 2016). The platform jackets surveyed here were reefed in 2020. The fishes surveyed in this study are, therefore, likely former residents of nearby natural reefs such as Hin Bai that have been attracted to the RJZ, and not the result of fish community productivity at the RJZ itself (Bohnsack, 1989; Bohnsack and Sutherland, 1985). Overfishing may therefore incur a net loss of fish abundance in the region (Scarborough Bull and Kendall, 1994). Long-term studies of fish productivity at RTRs are desirable, contextualised by the results of shorter-term investigations like the study presented here, provided that productivity can be delineated from attraction or aggregation and the residence times of fishes at RTRs can be quantified (Fowler et al., 2015a; Szedlmayer and Schroepfer, 2005). Nevertheless, with adequate management and continued monitoring alongside local natural systems

(Bond et al., 2018; Streich et al., 2017; Wilson et al., 2003), the relatively high biomass density and large size of fishes surveyed here could provide the foundation for future productivity at the RJZ, incurring a net benefit for fisheries in the western GoT.

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CRediT authorship contribution statement

Edward C.P. Sibley: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alethea S. Madgett:** Writing – review & editing, Supervision, Project administration. **Travis S. Elsdon:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Michael J. Marnane:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Euan S. Harvey:** Writing – review & editing, Resources, Methodology, Investigation, Data curation, Conceptualization. **Se Songploy:** Investigation. **Jes Kettradad:** Investigation. **Paul G. Fernandes:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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