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Spawning aggregation of bigeye trevally, *Caranx sexfasciatus*, highlights the ecological importance of oil and gas platforms

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A R T I C L E I N F O

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A B S T R A C T

There is growing interest in understanding the ecological benefits of oil and gas structures. This is the first reported case of the spawning aggregation and mating behaviour of bigeye trevally, *Caranx sexfasciatus,* associated with an oil and gas platform, demonstrating that oil and gas jackets are capable of not only attracting large aggregations of fish, but can provide suitable conditions for reproductive purposes. Fish spawning aggregations (FSAs) are highly vulnerable events that are vitally important for the persistence of many fish species. Urgent protection and conservation of FSA sites is required to secure them from the threat of overfishing. The findings of this study bring into question the management strategies required for oil and gas structures, particularly related to removal during decommissioning, or where structures are left in place and safety exclusion zones no longer apply. These aggregations and behaviours were captured using underwater stereo-video Remotely Operated Vehicle (ROV) methods, allowing for detailed observations.

1. Introduction

As numerous oil and gas structures are now at, or nearing, the end of their intended life (Lemasson et al., 2021), there is a growing interest in understanding the environmental effects of various decommissioning options, such as full removal, reef or leave in situ. Descriptions of how fish utilise the vertical structure created by platform jackets (platforms) can provide insights into possible outcomes of decommissioning alternatives (Bull and Love, 2019). Benefits of leaving structure in situ include demonstrated evidence that oil and gas infrastructure can support a high abundance and diversity of sessile invertebrates and fish (e.g., Harvey et al., 2021) as well as increased fishery production (Claisse et al., 2014; Friedlander et al., 2014; Elden et al., 2022).

Fish Spawning Aggregations (FSAs) are critical life-cycle events involving the temporary gatherings of conspecific fish for the sole purpose of reproduction (Domeier, 2012). Although few FSA sites are protected, potentially because they largely remain unidentified, (Binder et al., 2021), they are a focal point for fisheries management and marine conservation on a global scale and are frequently recognised within the language of national and multinational management strategies (Skubel, 2016). For example, the annual spawning aggregation of *Caranx sexfasciatus* (bigeye trevally) inside Cabo Pulmo National Park in Mexico has become an icon of the well documented recovery of this marine-protected area that attracts thousands of divers and generates millions of dollars for the surrounding community each year (Erisman et al., 2017). FSAs are often predictable in time and space, largely due to their interaction and dependency on habitat features and ocean dynamics that create links through ocean food-webs (Erisman et al., 2018).

Intrinsic environmental characteristics make FSA sites ideal locations to maximise reproductive success, such as particular geomorphology and oceanography features (Chollett et al., 2020). Platforms create a high vertical relief in the water column, which

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increases exposure to ocean currents (Harvey et al., 2021). They act as "pinnacles", identified as a FSA site characteristic for multiple species (Flynn et al., 2006; Kobara et al., 2013; Robinson and Samoilys 2013). The hard substratum extending through the water column provided by the platforms has been reported to attract fish in large numbers (Fish Aggregating Devices (FAD) effect) (Snodgrass et al., 2020), and biotic and abiotic conditions are reported to vary from platform to platform (Elden et al., 2019). It is possible that these man-made structures form a system of interconnected reef environments through the planktonic dispersal of the pelagic stages of organisms by ocean currents (Molen et al., 2018).

As well as providing suitable physical characteristics, various studies have described platforms as de facto marine protected areas (MPAs) (Friedlander et al., 2014; Elden et al., 2019). The statutory 500 m exclusion safety zone around offshore installations in the Gulf of Thailand restrict vessel access, providing protection from all fishing types (commercial overfishing has been identified as the greatest threat to FSA (Rhodes and Warren-Rhodes, 2005)). If the combination of broad physical characteristics and fishing protection contribute to the development of viable spawning grounds, platforms potentially have significant ecological value.

Bigeye trevally is an economically important pelagic fish distributed widely throughout the tropical and subtropical waters of both the Indian and Pacific Oceans (Juan Violante-González et al., 2020). Bigeye trevally has the price category of "high" on Fishbase (Sumaila et al., 2007) and are frequently combined in the Family Carangidae (jacks, pompanos, jack mackerels, runners, and scads) for fish market reporting. In the "Fish Marketing Organization" Thailand's aquatic price as of May 2022, the Carangidae are valued at 40 Thai baht/kilogram (Fish Marketing Organization, 2022). Bigeye trevally is also popular with anglers, with the species rated as an excellent gamefish in larger sizes (Thai National Parks, 2022). A study by Rajesh et al. (2017) described the selection of bigeye trevally for Capture Based Aquaculture in Karnataka, India, due to the good numbers of wild stock, fast growth and the good market price. They were considered a suitable species for mariculture in cages areas in Karnataka, reducing the pressure that now exists to procure seabass and snappers from hatcheries as well as from the wild.

Information on the population status, reproduction, movement patterns and habitat use of bigeye trevally is limited. For example, Low (2018) described bigeye trevally as "uncommon and poorly known" in Singapore. The species population doubling time is 1.4–4.4 years, categorised as "medium" resilience (Froese et al., 2017). Resilience is defined as the ability of a species population to recover after a perturbance and is reported as: "very low" (>14 years), "low" (4.5–14 years), "medium" (1.4–4.4 years), or "high" (<14 months), calculated using parameters, such as growth coefficients, life-span data, exploitation and recorded maximum lengths. The fishing vulnerability of bigeye trevally is defined as "moderate to high", and climate vulnerability defined as "high to very high" (Cheung et al., 2005; Jones and Cheung, 2017; Froese and Pauly, 2022). In contrast, Duffy et al. (2019) developed a Productivity-Susceptibility Analysis (PSA) as part of an ecological risk assessment (ERA) to assess the relative vulnerability of data-limited non-target species to the impacts by fishing (overexploitation). Bigeye trevally was identified as the least vulnerable incidentally caught species for three set types for tuna purse-seine fishery in the eastern Pacific Ocean (EPO).

Fishing and diving around offshore rigs, in countries where it is allowed, is a major component of the local tourism industries (Elden et al., 2019). Bigeye trevally often form large, stationary, daytime schools, but usually tend to be solitary at night when feeding (Allen and Erdmann, 2012). Adults inhabit coastal and oceanic waters associated with reefs and have a depth range of 1–96 m (Mundy, 2005). Spawning has been reported to occur during the daytime around full moon periods (Sala et al., 2003). Fish aggregate in large schools near the surface before spawning. The males rapidly (for a few minutes) become dark in colour, almost black, and the female retains normal silvery colour. A male station himself below the female, with pairs increasing their swimming speed and breaking off from the main group. The male chases off any other fish that approach the pair. The male nuzzles the gonopore of the female, releasing a small cloud of gametes that disperses within seconds. Once spawning has ended, the male swims horizontally for a few seconds before reverting to normal colour and returning to the school (Sala et al., 2003; Mitcheson and Colin, 2012; Allen et al., 2019). Sala et al. (2003) reported the process of bigeye trevally spawning in the Gulf of California, where schools aggregated at specific reefs in the summer to spawn. Spawning aggregations varied in size and individuals varied in length, ranging 60–80 cm.

How oil and gas structures modify/influence the movement patterns (migration, dispersal, foraging, spawning/breeding sites) of mobile species and the contribution that associated breeding fish make to regional reproductive output and populations elsewhere are priority research questions derived from expert elicitation on the influence of infrastructure on seascape connectivity (McLean et al., 2022). Debate remains as to the extent/importance of the contribution to stock productivity (Cowan and Rose, 2016; Streich et al., 2017; Downey et al., 2018) and the overall ability of oil and gas structures to modify marine ecological structure and functioning (Elliott and Birchenough, 2022).

This study was part of a wider scientific survey to sample the fish assemblage associated with oil and gas platforms in the Gulf of Thailand (GoT) using high-definition stereo-video Remotely Operated Vehicle (ROV) to assess the value of these offshore platforms as coral reef fish habitat (Harvey et al., 2021). Stereo-video technology can provide repeatable and consistent fish counts, accurate lengths and meaningful insights into fish behaviour (Harvey et al., 2001a, b; Goetze et al., 2017). However, this approach has rarely been used to examine spawning aggregations, and to an even lesser extent, to investigate spawning behaviours (Rastoin-Laplane et al., 2020). If oil and gas platforms are found to facilitate FSAs, appropriate site management and conservation would offer an effective and pragmatic approach to regenerate fished populations.

2. Materials and methods

In summary, an observation-class ROV with a tether management system (TMS), fitted with an underwater stereo video camera system, was used to record fish at a non-operational oil and gas platform located within the GoT. The stereo-video system, calibration methods and image analysis are discussed in detail in Harvey et al. (2021). The structure (11 $\times$ 11 m at the top and 21 $\times$ 21 m at the bottom) was positioned on unconsolidated soft sediment habitat, located ~150 km from natural reef and shoreline, in 65.8 m water depth. Cameras were set to record at 60 frames per second in a full high-definition resolution (1920 $\times$ 1080 pixels, progressive scan). The higher recording rate was used to minimise potential motion parallax associated with fish and the ROV moving simultaneously.

The two stereo-video systems were calibrated in water before and after the fieldwork following well established protocols and guidelines (Harvey and Shortis, 1998; Shortis and Harvey, 1998; Shortis et al., 2009; Boutros et al., 2015). Images were processed through the SeaGIS CAL software package,[1] which provides a general photogrammetric bundle adjustment for stereo camera systems. This system allowed an accurate measurement of fish length with a high level of accuracy and precision (to within 1% of the true length (Harvey et al., 2010). All counts and measurements of fish were made in EventMeasure Stereo.[2]

3. Results

A spawning aggregation (183 individuals) of bigeye trevally was

[1] https://www.seagis.com.au/bundle.html.
[2] https://www.seagis.com.au/event.html.

observed on March 7, 2018, five days after the full moon. The aggregation was identified serendipitously during a scientific survey to sample the fish assemblage associated with oil and gas platforms in the GoT using high-definition stereo-video ROV.

In this study, the length of bigeye trevally ranged from 44 to 74 cm. Bigeye trevally reach sexual maturity when they are around 42 cm in length (Whitfield, 1998; Froese and Pauly, 2022). As they mature, dark coloured bands, that are present on the body of juveniles, fade and the body colour shift to a silvery blue. This adult coloration was observed in all the fish observed in video imagery as part of this study (Fig. 1a–j).

Bigeye trevally were observed between the platform legs forming an aggregation at ~45 m depth, with individuals swimming in a circular motion (Fig. 1a–c). Once the aggregation was formed, bigeye trevally were observed to increase swimming speed, weaving in and out of the structure with some individuals turning dark/black in colour (Fig. 1d and e). Male-female pairs then left the main aggregation, with the dark coloured male swimming directly below the female (Fig. 1f, g, h). Pairs remained nearby the structure, but well separated from each other (Fig. 1h). Gamete release from spawning pairs was identified, where gametes extended into the water column for several seconds before dispersing (Fig. 1i and j).

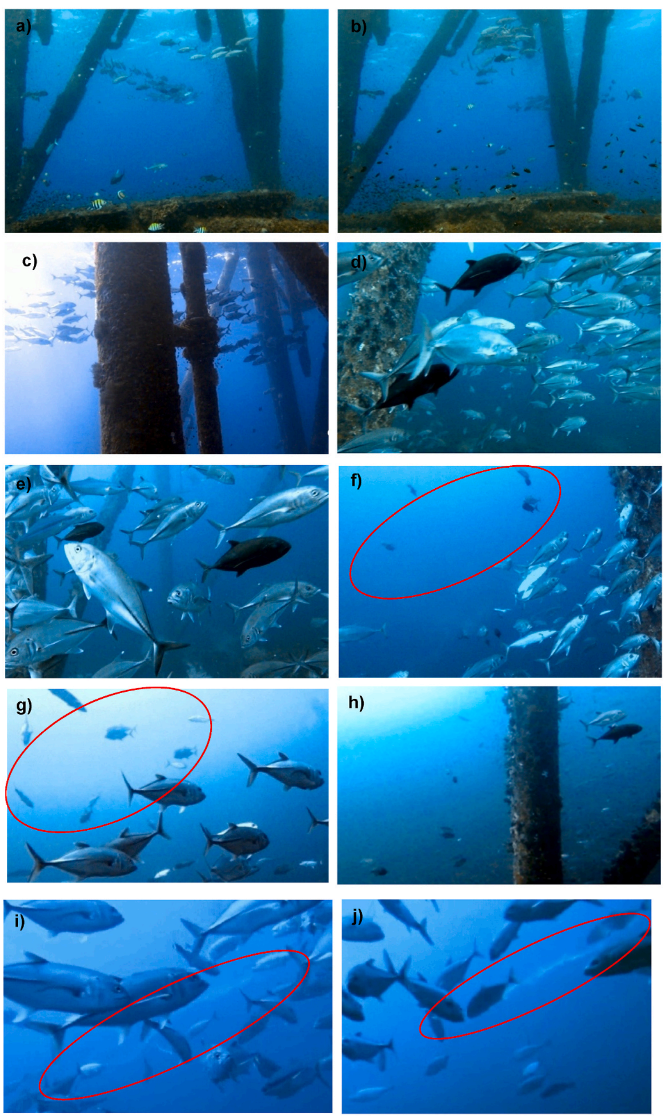

Fig. 1. Spawning aggregation of bigeye trevally at an oil and gas platform in the central Gulf of Thailand: **a), b)** Smaller groups of bigeye trevally collecting inside the structure and forming a larger aggregation (183 individuals), swimming in a circular motion; **c)** Formation of the spawning aggregation; **d), e)** Males rapidly change colour from a silvery/blue to dark/black prior to spawning; **f), g)** Spawning pairs leaving the main aggregation, with the male swimming directly below the female (red circles); **h)** Spawning pairs remaining nearby the structure; **i), j)** Gamete release from a spawning pair. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Spawning activity occurred throughout the entire survey period (07:30–11:09). A small number of other species (including *Elagatis bipinnulata* (rainbow runner), *Seriola lalandi* (yellowtail amberjack) and *Carangoides gymnostethus* (bludger trevally) were observed as solitary individuals in the main aggregation which could have been attracted to the nutrient-dense food source provided as an influx of eggs.

4. Discussion

The description of a specific spawning site for bigeye trevally in the GoT and spawning aggregations associated with oil and gas structures worldwide, have, to our knowledge, not been previously reported. In general, there is limited published information on bigeye trevally spawning, but the aggregation in this study is smaller than previously reported in the Gulf of California (Sala et al., 2003) and Mexico (Erisman et al., 2017). It has however been recognised that carangid spawning aggregation fish density is highly variable, as many species of carangids normally exist in schools before spawning (Mitcheson and Colin, 2012). The smaller aggregation size observed in this study may be due to the platform's distance from natural reef (~150 km), where there would be a lower density of fish. Bigeye trevally spawning has been reported to occur between July and September in the east Pacific, and November to March in South Africa (Jayakumar et al., 2017), suggesting that the spawning time reported in this study was on the later side of the wider regional spawning period.

Bigeye trevally has been identified as an abundant species associated with oil and gas platforms worldwide. A study by McLean et al. (2019) reported bigeye trevally to be the most abundant species at an operational platform in north-west Australia. Like this study, the platform was situated in tropical waters at a remote region dominated by soft sediment with an enforced exclusion zone, and bigeye trevally were more abundant at depths of 25–50 m. Pelagic spawning aggregations have previously been reported around a topographic feature and/or close to the surface (Afonso et al., 2008; Karnauskas et al., 2011; Erisman et al., 2017). A study by Torquato et al. (2017) on the taxonomic diversity of fish aggregations at oil and gas platforms in north-eastern Qatar reported Carangidae as the most diverse family (10 species), where 379 bigeye trevally individuals were identified at 9 locations within the Al Shaheen oil field using ROV inspection videos.

There is limited published information on spawning aggregations associated with oil and gas platforms, and to the author's knowledge, only three events been previously reported at a platform during a single study. A study by Friedlander et al. (2014) observed the spawning of red snapper, *Lutjanus dentatus*, and yellow jack, *Caranx bartholomaeion*, at an oil and gas platform off Cape Lopez, west central Africa. Male and female red snapper swam together from deeper water towards the surface, forming a spiral, and swimming apart while releasing eggs and sperm at 10 m depth. Two mass spawning events were identified for red snapper, one inside the structure and one outside the structure. Like the bigeye trevally spawning event described in this study, pair spawning was also observed for yellow jacks. Schools of up to several hundred individuals were formed near the surface. Males changed colour from silver to dark/black and spawning pairs swam together away from the school. Gamete release was not observed for the yellow jack spawning aggregation, but the courtship behaviour described has been identified for other species of jacks. The study concluded that platforms are likely sources for the replenishment of other platforms and the scarce reefs in the region and could be of great value to fisheries conservation for commercially harvested fish species.

Information on relationships between fish and habitats is essential for informing fisheries management and conservation. Understanding these relationships enables natural and anthropogenic impacts to be assessed (McLean et al., 2016). The identification of spawning sites can be used to protect sensitive habitats, establish marine protected areas, or assess recruitment (Bauer et al., 2014). It has been recognised that their protection will build natural replenishment and resilience on a broader ecosystem scale (Pittman and Heyman, 2020). For example, study by Da Silva et al. (2014) reported a large spawning aggregation of giant trevally within a community declared no-take zone on the eastern point of Vamizi island. Although the physical release of gametes was not observed, indirect evidence commonly used to infer spawning activity (observed courtship behaviours including fish chasing and coloration changes), indicate these fish were in the process of spawning. This represented the first identified spawning location for giant trevally in the Western Indian Ocean, reinforcing the importance of the no take designation at this site.

Fish biologists have highlighted the urgent need to establish large-scale programs to better monitor, manage and conserve spawning events (Erisman et al., 2017; Grüss et al., 2018; Heyman et al., 2019). The International Union for Conservation of Nature (IUCN) World Conservation Congress recommended governments create management measures that would sustainably protect reef fish and their spawning aggregations, as well as directing non-governmental organisations and fishing management organisations to take up the issue (Mitcheson and Colin, 2012; Skubel, 2016; Fulton et al., 2020). Achieving this goal will require a range of non-invasive, easily repeatable methods available to decision makers to assess the status of spawning events and in this study, stereo-video technology has provided an effective tool to generate the data needed to characterise and manage spawning aggregations. This agrees with a study by Rastoin-Laplane et al. (2020), who found that stereo-video presents great potential for the long-term monitoring of spawning.

This study contributes to the knowledge base of oil and gas structure's importance to population connectivity and production and shows that platforms are capable of not only attracting large aggregations of fish, but can provide suitable conditions for reproductive purposes, contributing to the "attraction vs production" debate (Elden et al., 2019). The attraction and aggregation of fishes at a predictable time can, however, result in them being more easily caught, potentially resulting in further declines in overexploited fisheries (Golbuu and Friedlander, 2011; Claisse et al., 2014). The supply of reef fish larvae from the open ocean to reefs is vital for the persistence of local fish populations and the findings of this study suggest that structures modify/influence the movement patterns of mobile species and can contribute to regional reproductive output. It is therefore crucial to protect FSA sites, as protecting one area can replenish numerous species across their ranges.

Focussed management strategies for FSA sites and decommissioned oil and gas structures are lacking (Sadovy de Mitcheson, 2016; Heyman et al., 2019). Although live platforms in the GoT currently impose a 500 m exclusion safety zone, it is unclear what, if any, management measures would be enforced for platforms that are reefed or remain in situ following decommissioning. Whether larvae are dispersed over hundreds of km or only few km depends on biophysical interactions between larvae and their environment (Mayorga-Adame et al., 2017), and at the platform location, the fertilised eggs and larvae may travel to the nearby natural reef (~150 km away) or mangrove forests. The findings of this study contribute to the increasing evidence base of the ecological value of oil and gas structures and raises questions on how we should manage these sites once the safety exclusion zones no longer apply.

CRediT authorship contribution statement

Alethea S. Madgett: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Euan S. Harvey:** Writing – review & editing, Supervision, Software, Project administration, Funding acquisition, Formal analysis, Data curation. **Damon Driessen:** Writing – review & editing, Software, Formal analysis, Data curation. **Karl D. Schramm:** Writing – review & editing, Software, Formal analysis, Data curation. **Laura A.F. Fullwood:** Writing – review & editing, Software, Formal analysis, Data curation. **Se Songploy:** Writing – review & editing. **Jes Kettratad:** Writing – review & editing. **Paweena Sitaworawet:** Writing – review & editing. **Sarin Chaiyakul:** Writing – review & editing. **Travis S. Elsdon:** Writing – review & editing, Project administration, Funding acquisition. **Michael J. Marnane:** Writing – review & editing, Project administration, Funding acquisition, Data curation.

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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