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ASSESSING THE PERFORMANCE OF ARTIFICIAL REEFS AS A FISHERIES MANAGEMENT TOOL IN THE GULF OF THAILAND

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ABSTRACT: This study assesses the effectiveness of artificial reefs as fisheries management tools in the Gulf of Thailand, a region with high levels of fishing and tourism. Fish assemblages representing various functional groups and trophic levels, were compared between two artificial and two natural reefs. Fish abundance data was collected using underwater visual censuses during timed-swim surveys, covering an approximate area of 1,200 m² per transect. Surveys yielded a total of 12,522 fish counts from 68 transects. Statistical analyses were performed to investigate site-specific community structures and habitat preferences. These revealed significant compositional dissimilarities, both amongst and between reef types. *Lutjanus*, *Diagramma* and *Plectorhinchus* showed a preference towards artificial reefs, indicating the potential value of artificial reefs in supporting mid-trophic species of economic importance to fisheries. Conversely, *Labroides* and *Hemigymnus* favoured natural reefs, suggesting possible limitations of artificial reefs in supporting entire reef ecosystems. *Lutjanus* also exhibited a strong preference towards shipwrecks over concrete structures, possibly highlighting the importance of unique structural design and material in influencing species distribution. This study highlights the necessity of considering ecological characteristics, target species and deployment objectives of future artificial reefs. Although they may benefit certain valuable species, their role in maintaining biodiversity is limited, reinforcing the need for natural reef conservation. This research offers insight into the role of artificial reefs as fisheries management tools, acting as potential habitat refuge, whilst also highlighting the importance of strategic planning and further research for enhancing their ecological and conservation effectiveness in the Gulf of Thailand.

Key words: Artificial Reefs, Fisheries Management, Fish Communities, Functional Groups, Conservation, Coral Reefs, Habitat Complexity

INTRODUCTION

Over the last century, coral reefs have faced numerous anthropogenic stressors across the globe, resulting in habitat degradation, and a decline in reef health (Wilkinson 1999; Jackson *et al*. 2001; Sandin *et al*. 2008; Coker *et al*. 2014). Consequently, fisheries supported by these structurally complex ecosystems have also suffered declines worldwide (Jones *et al*. 2004; Paddack *et al*. 2009; Pratchett *et al*. 2011). Reef fish populations, particularly of mid to higher trophic species, have also been heavily exploited in an unsustainable manner through overfishing (Newton *et al*. 2007; Abesamis *et al*. 2014) with reductions being well documented for a variety of species across the tropics (Hughes *et al*. 2003; McLean *et al*. 2010; Guardia *et al*. 2018).

Artificial reefs are broadly defined as submerged structures, deployed on the seabed, that mimic certain characteristics of natural reefs (Jensen 1998). An artificial reef (hereinafter called ‘AR’) may form naturally, or accidentally - in the case of unplanned shipwrecks. Combined with the intentional deployment of ARs using vessels (ships, aeroplanes, cars etc.), or other materials produced artificially (*e.g*. tires, fibreglass, steel, concrete etc.) these ARs have become a popular method used as a fisheries management tool (Bohnsack and Sutherland, 1985; Chua and Chou 1994; Kheawwongjan and Kim 2012; Tynyakov *et al*. 2017), particularly in the Gulf of Thailand since the inclusion of the Department of Fisheries Artificial Reef Program (Supongpan 2006; Bauer *et al.* 2023). Topographic complexity, structural habitat complexity and vertical relief that are provided from different forms of AR environments have been strongly linked factors associated with increased fishery biomass and variation in community structure (Almany 2004; Walker *et al*. 2009; Sensurat-Genc *et al*. 2022). Despite this, research aimed at assessing and comparing their performance as a conservation and management tool, is often insufficient, as follow-up studies that evaluate how well they meet the project's objectives are often neglected (Crabbe and McClanahan 2006; Arena *et al*. 2007; Becker *et al*. 2018; Sensurat-Genc *et al*. 2022). This is commonly a result of their inaccessibility, due to location and/or submerged depth (Sreekanth *et al*. 2019). Furthermore, faunal assemblages may be challenging to accurately compare between areas where there is significant variation in abiotic/biotic factors existing between ARs and natural reefs (Hunter and Sayer 2009; Lemoine *et al*. 2019). Consequently, fisheries and other conservation management efforts that employ the use of ARs often lack the supporting empirical evidence to evaluate whether or not the goals established prior to their deployment have been achieved.

With its ease of access, and high number of reefs ranging from shallow fringing reefs to deeper isolated pinnacles, Koh Tao is a major hotspot for tourism, often associated with diving and snorkelling (Lamb *et al*. 2014; Scott *et al*. 2017; Bauer *et al*. 2023). Both commercial and local fishing vessels also frequent areas surrounding the island (Wongthong 2013), where mesopredatory species and higher trophic level predators (HTLPs) commonly aggregate. In addition to Koh Tao's many natural reefs, ARs have also been deployed following similar objectives to those listed above (Supongpan 2006). These include a number of hollow, concrete cubes - commonly deployed in stacked formations, as well as intentionally sunk shipwrecks, including the *HTMS Sattakut*.

AR programs were first established in Thailand in 1978, with a number of these having been deployed within the Gulf of Thailand (Sinanuwong *et al.* 1986; Supongpan 2006, Kheawwongjan and Kim 2012). Many of these are located around the island of Koh Tao – an area that experiences high levels of tourism, diving, fishing and coastal development (Szuster and Dietrich 2014; Wongthong and Harvey 2014; Scott *et al*. 2017). Both purposefully deployed shipwrecks, and numerous ARs constructed using large, hollow cement cubes have been placed within close proximity to nearby natural reefs around the island. Purposes for their deployment include; the provisioning of substrates for coral recruitment, to relieve stress from divers caused to natural reefs, to rehabilitate coastal fishing areas and support local fisheries for artisanal fishing, provide coastal protection, and as other fisheries management tools (Sinanuwong *et al*. 1986, Chou 1997; Seaman, 2007; Bauer *et al.* 2023). Despite their use, there remains a lack of in-depth assessments of their local performance from the Koh Tao region, with particular regard to supporting fish assemblages. A number of previous studies have compared trophic structures found on artificial reefs to that of natural reefs (*e.g*. Arena *et al*. 2007; Consoli *et al*. 2015, Sreekanth *et al.* 2019), however few studies have been conducted in recent times from within the Gulf of Thailand (Harvey *et al*. 2021; Monchanin *et al*. 2021; Bauer *et al.* 2023), particularly where the performance of different AR designs have not been compared.

The current study aims to evaluate and assess the performance of ARs used in the Gulf of Thailand, with a focus on studying their effectiveness as fisheries management tools. To achieve this, the relative abundance of fish assemblages belonging to differing functional groups and trophic levels were selected and compared between natural and AR environments. Through underwater visual census (UVC) conducted by divers, four types of reefs were assessed including, two types of ARs, and two natural reefs – independently located nearby to one of each AR. Other studies have suggested ARs offer distinct features that contribute to supporting different fish communities (*e.g*. Arena *et al*. 2007; Mills *et al*. 2017; Lemoine *et al*. 2019). Therefore, the current study's hypotheses are that dissimilarities will exist between local reef types, with ARs supporting significant assemblages of certain functional groups of fish. The current study serves as a preliminary assessment of the effectiveness of locally deployed AR structures, and their design-specific values in supporting fish assemblages for the conservation and management of local fisheries. Findings from this study may help guide future efforts to manage fisheries and conserve biodiversity in the Gulf of Thailand, as well as inform decisions on the designs and deployment of ARs in the region to meet specific aims and conservation goals.

MATERIALS AND METHODS

Study location

The current study was carried out around the island of Koh Tao, in the Gulf of Thailand (10.10980°N, 99.81180°E) (Fig. 1). The *HTMS Sattakut* and the AR concrete cubes used in the current study, were both positioned close to natural reef pinnacles, isolated from other reefs (Fig. 2). Comparisons between natural reefs and ARs are often obscured due to differences in the size, age, and isolation of the reefs (Carr and Hixon 1997). For comparisons and ecological assessments between reef types during the current study, sites were chosen based on similarities in depth (maximum depths between 25-30m across all sites), reef size, relative distance to shorelines, connectivity with other reefs, and general reef health/condition.

The two natural reefs selected for this study were situated within close proximity (between 50-100m) to their neighbouring AR. These two ARs, along with their neighbouring natural reefs, therefore created a model study system for comparing fish assemblages between respective reef types. Through comparative analyses, the habitats provided by different AR types (wrecks vs. concrete structures) as well as the variance in fish community structures across these environments could be measured.

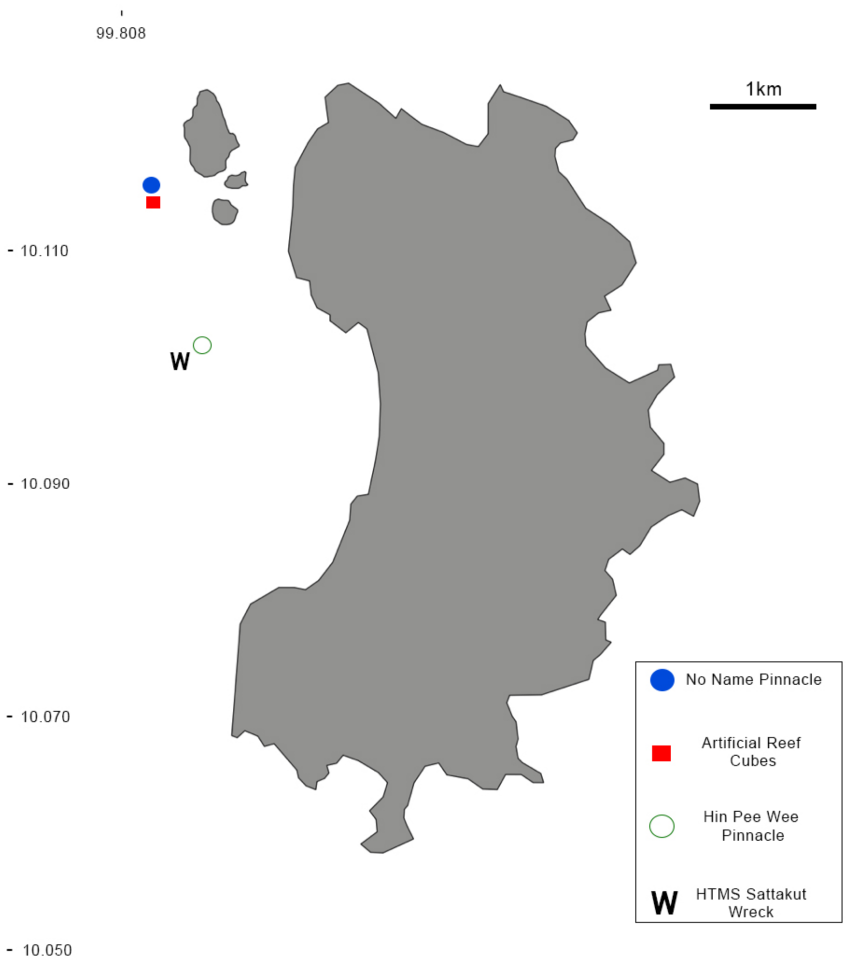

Figure 1. A map of the surveyed sites, located near Koh Tao, Thailand. Sites include both natural reef sites (No Name Pinnacle, and Hin Pee Wee Pinnacle), and both artificial reef (AR) sites (Artificial Reef Cubes, and HTMS Sattakut Wreck).

Estimating fish density

A predetermined species list was generated for all surveys, including different fish genera that were representative of a range of functional groups (e.g. herbivores, mesopredators, higher-trophic level predators etc.) and ecological niches. Although smaller genera such as *Pomacentrus* and *Neopomacentrus* were not included, it is important to note that members of functional groups typically smaller in size are likely to be less affected by local fishing efforts. Given the aims of the current study, a focus was applied to larger fish, which are more vulnerable to fishing (both directly and as bycatch). Separations of fish genera that occupied different functional groups were further separated based on size (*e.g.* *Epinephelus* and *Plectropomus*). Population density estimates were calculated for each of the four sites, using abundance data gathered during fixed timed-swim transects, conducted from November 2022 – November 2023. Surveys were regularly conducted between all four sites throughout the year, controlling for any seasonal effects. Surveys across all sites adopted an eight minute timed-swim survey, whilst maintaining the same swimming speed (approximately 12 m/min), to ensure consistency in area covered per survey. An estimated area of 1,200m^2 was covered during each survey. This was calculated by measuring the distance covered during multiple pilot timed-swim surveys. Only fish within an estimated ten metre radius of the diver were included in abundance counts, allowing for the calculation of an estimated total survey area. Population density estimates were derived by calculating the mean abundance of fish per 1,200 m^2. The protocol followed was adapted from the timed-swim method (described by Hill and Wilkinson 2004), Depths were similar across all four sites. The use of belt transects using transect lines was avoided in order to minimise disturbance of fish within the survey area due to the placement of transects, as has been previously suggested (Schmitt *et al*. 2002; Irigoyen *et al*. 2018). A minimum of 15 surveys were completed at each site, with a total number of 68 surveys conducted across all sites.

Statistical analysis

Fish genera belonging to the same families, and of similar ecological roles were grouped together for statistical analyses. Community structure and species preferences across different reef types were first analysed. A fourth-root transformation of data was applied to reduce the influence of highly abundant fish species (*e.g*. large-schooling species). Initially, Non-metric multidimensional scaling (NMDS) analysis based on Bray-Curtis distance matrix was used to assess community structure differences between reef types (artificial vs natural), as well as sites. Permutational Multivariate Analysis of Variance (PERMANOVA; Anderson 2003) was conducted to further investigate community structure differences highlighted by NMDS. This non-parametric statistical test is particularly well-suited when comparing fish community structures using ecological data, which often do not meet the assumptions of parametric tests, such as normal distribution of residuals and homogeneity of variances (*e.g*. Simon and Pinheiro 2013; Lemoine *et al.* 2019).

Following the PERMANOVA, a similarity percentages (SIMPER) analysis was used to identify species of fish that contributed most significantly to the observed dissimilarities between reef types and AR sites.

Sites were grouped together based on reef type (artificial vs natural reefs) for certain analyses. To further explore the preferences of species identified by the SIMPER analysis towards reef types, Mann Whitney U tests were used to specify any differences found between reef types and AR sites. These tests were useful for evaluating whether different designs of ARs may influence species distribution.

This combination of statistical analyses provided a robust framework for assessing broad patterns of species distribution across reef types and the specific preference both between and within reef types. All statistical analyses were carried out using RStudio 1.1.494 (RStudio Team 2023).

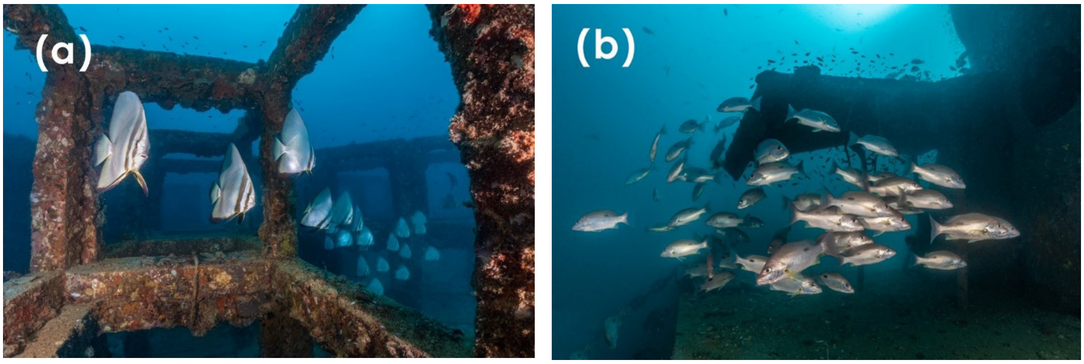

Figure 2. Images demonstrating fish assemblages present on different artificial reef types deployed in Koh Tao, Thailand, including (a) artificial reef cubes, and (b) the HTMS Sattakut shipwreck.

RESULTS

During the study, a total of 12,522 individual fish counts were included from 68 transects, recorded for 23 species, across 17 families. An average density of 240±12.65 fish per 1,200 m^2 was recorded during surveys conducted at the shipwreck, compared to 202±19.79 per 1,200 m^2 at the AR cubes, as well as 184±15.50 per 1,200 m^2 and 102±6.76 per 1,200 m^2 on both natural reef sites. Average fish population densities were calculated for each genus, across all four study sites (Fig. 3). A full table of fish densities is provided in Appendix A.

Community Structure

Non-metric multidimensional scaling (NMDS) analysis based on Bray-Curtis distance matrix revealed differences in community composition across reef types and sites (Fig. 4). Natural reefs were distinctly separated from artificial reefs along the x-axis (NMDS1). Similar patterns were shown for sites, with distinctive clusters for each site (Artificial Reef Cubes, Hin Pee Wee, HTMS Sattakut, No Name Pinnacle). A two-way PERMANOVA analysis conducted on a Bray-Curtis distance matrix confirmed significant differences in community composition across sites (pseudo-F = 18.90, df = 2, $p < 0.001$) and reef types (pseudo-F = 22.47, df = 1, $p < 0.001$).

Further insights were gained from the SIMPER analysis for the observed differences in community structures between artificial and natural reefs. This demonstrated the cumulative contributions of the most influential species in distinguishing between artificial and natural reef communities (Table 1). The analysis revealed that *Lutjanus* were the primary genus contributing to this difference (accounting for approximately 30.46% of the dissimilarity). Significant contributions were also made by *Sphyraena* (11.33%), *Diagramma/Plectorhinchus* (6.76%), *Cephalopholis/Epinephelus* <30cm (5.22%), *Carangoides* (5.03%), *Siganus* (4.35%), *Hemigymnus* (3.85%), and *Lethrinus* (3.66%).

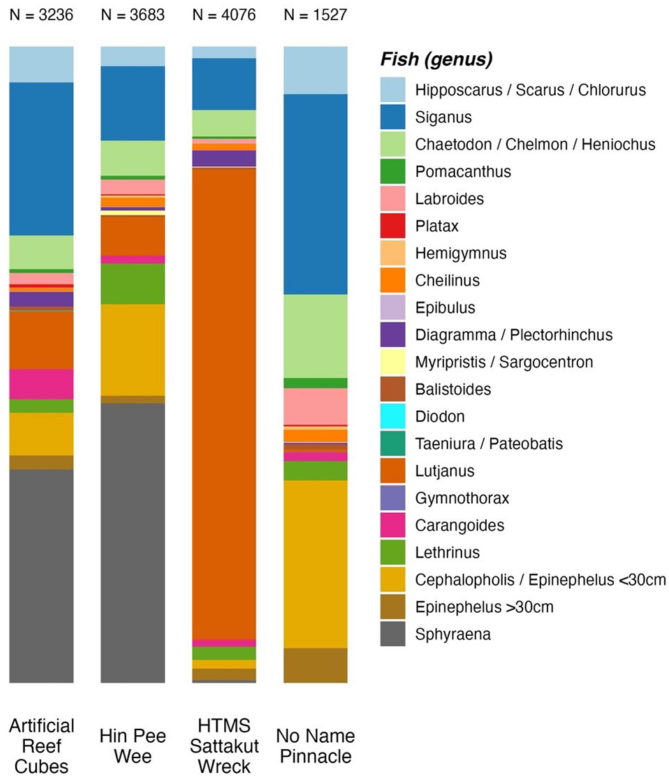

Figure 3. Stacked bar charts representing density distribution of different genera across study locations. A representation of the average population density of fish genera included during surveys conducted at two natural reef sites (Hin Pee Wee, and No Name Pinnacle), as well as two artificial reef sites (HTMS Sattakut shipwreck, and Artificial Reef Cubes).

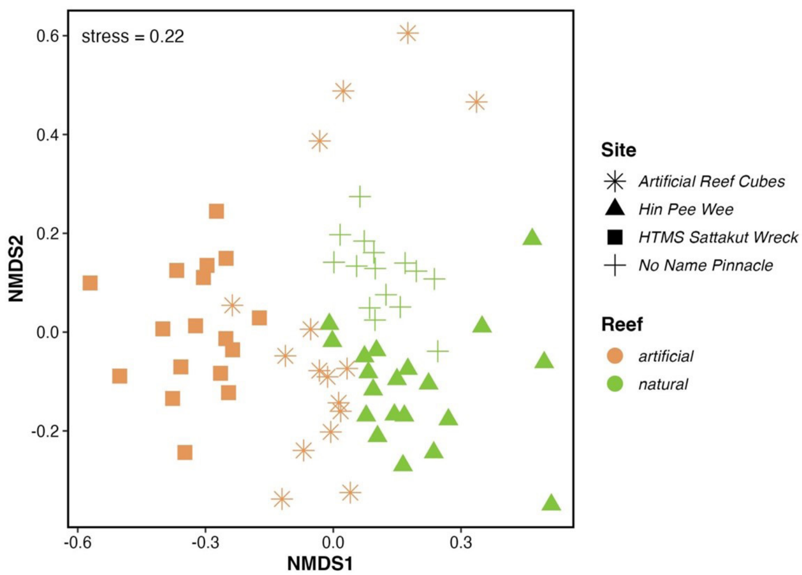

Figure 4. Two-dimensional non-metric multidimensional scaling (NMDS; stress 0.22) of community composition based on Bray-Curtis distance matrix for 21 genera of fish obtained across four different reef sites of Koh Tao.

Table 1. The cumulative and individual contributions of fish identified through SIMPER analyses as being the largest contributors to the observed dissimilarities between artificial and natural reef types.

Fish (genus)	Cumulative dissimilarity (%)	Individual dissimilarity (%)
Lutjanus	30.46	30.46
Sphyraena	41.79	11.33
Diagramma / Plectorhinchus	48.55	6.76
Cephalopholis / *Epinephelus* <30cm	53.76	5.22
Carangoides	58.79	5.03
Siganus	63.15	4.35
Hemigymnus	67.00	3.85
Lethrinus	70.66	3.66

Reef type habitat preferences

To further investigate habitat preferences and differences observed between reef types, Mann-Whitney U tests comparing fish abundance at artificial and natural reefs were separately conducted for each genus. Findings revealed intriguing preferences in species' habitat selection. Notably, fish genera including *Lutjanus* ($W = 1057.5$, $p < 0.001$) and *Diagramma / Plectorhinchus* ($W = 990.5$, $p < 0.001$) demonstrated a distinct preference towards AR types compared to natural reefs during pairwise comparisons between reef types (Fig. 5). Conversely, genera of fish including *Labroides* ($W = 219.5$, $p < 0.001$), *Hemigymnus* ($W = 318$, $p < 0.001$), *Cephalopholis / Epinephelus* <30cm ($W = 77$, $p < 0.001$), and *Pomacanthus* ($W = 407$, $p < 0.05$) all demonstrated a strong preference towards natural reefs during pairwise comparisons between reef types (Fig. 5). A full table of median density values for each reef type is provided in Appendix B.

Artificial reef design habitat preferences

Mann-Whi tney U tests comparing fish abundance at the two different artificial reef sites HTMS Sattakut and Artificial Reef Cubes yielded interesting results in accordance with habitat preferences between AR types. Notably, *Lutjanus* ($W = 0$, $p < 0.001$) and *Chelinus* ($W = 51$, $p < 0.01$) showed preferences towards the shipwreck compared to the AR cubes. Conversely, *Hipposcarus /Scarus/ Chlorurus* ($W = 225$, $p < 0.01$), *Siganus* ($W = 207.5$, $p < 0.05$), *Labroides* ($W = 0$, $p < 0.001$), *Sphyraena* ($W = 242.5$, $p < 0.001$), *Balistoides* ($W = 196$, $p < 0.05$), *Platax* ($W = 224$, $p < 0.001$, and *Cephalopholis/ Epinephelus* <30cm ($W = 242.5$, $p < 0.001$) all demonstrated significantly higher abundances on the artificial reef cubes, compared to the shipwreck. A full table of median density values for each artificial reef site is provided in Appendix C.

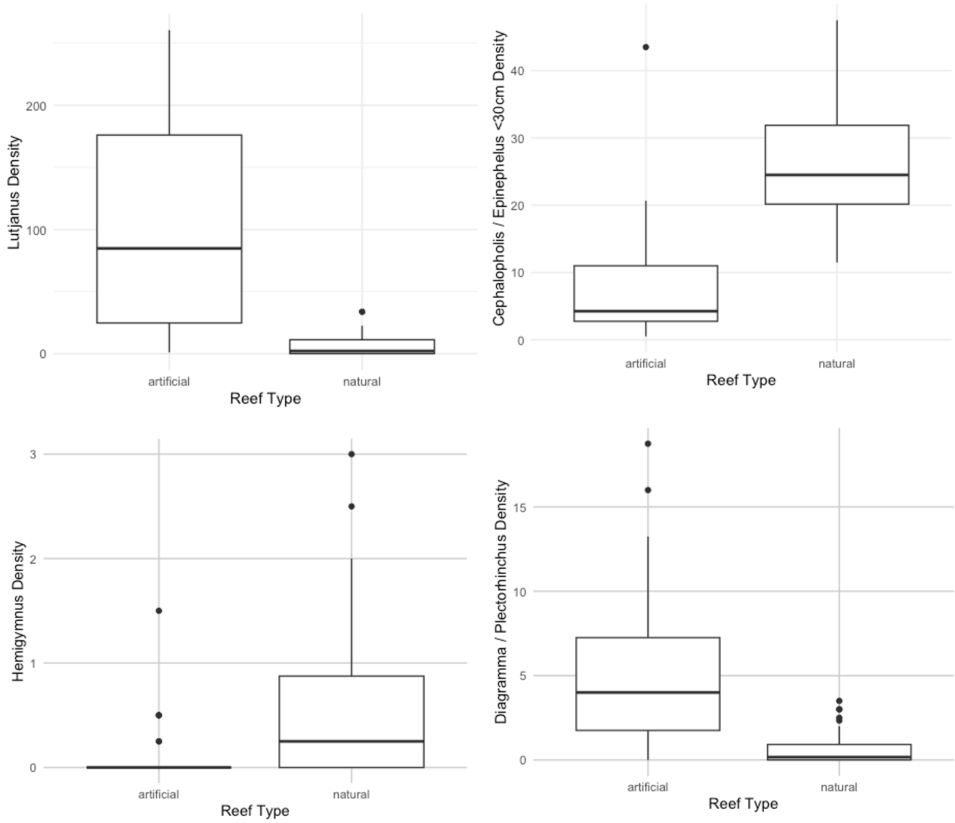

Figure 5. Boxplots displaying the density of genera identified as top contributors towards dissimilarities in community structures of reef types during SIMPER analyses, which also demonstrated a significant preference towards a particular reef type during Mann-Whitney U pairwise comparisons between artificial and natural reefs.

DISCUSSION

Community Structure

Dissimilarities in community structure observed between reef types include fish groups occupying a variety of different ecological niches. These findings offer crucial insights on a broad scale, as the observed dissimilarities could highlight that ARs may foster ecosystems distinct from those of natural reefs, even when located in close proximity. Previous studies have suggested that artificial reefs can support significantly different fish assemblages in comparison to natural reefs. Artificial reefs have been found to support different species compositions, sometimes exhibiting lower diversity compared to natural reefs, yet have been shown to support higher densities of certain fish. (Ambrose and Swarbrick 1989; Charbonnel *et al*. 2002; Gillanders *et al*. 2009; Cresson *et al*. 2014). Such findings may therefore suggest the limited efficacy of ARs when conservation goals include promoting similar levels of biodiversity and ecosystem structures to those of natural reefs.

Notably, the most pronounced differences were observed between the two types of ARs. This highlights the potential influence of material choice, structural design, and its associated structural complexity on community composition and species distribution, aligning with previous research (Fowler and Booth 2012). Previous studies have found that structures with greater vertical relief, such as steel shipwrecks, often support higher densities of fish and more diverse fish communities compared to lower relief structures (Ambrose and Swarbrick, 1989; Granneman and Steele 2015; Bulger *et al*. 2019). High-relief structures tend to attract transient predators and mid-higher trophic species due to their complex vertical habitats (Paxton *et al*. 2020; Barilotti *et al*. 2020; Burns *et al*. 2020). This may explain the high abundance of mid-trophic species including members of *Lutjanidae* at the Sattakut wreck, which offers lots of vertical relief and vertical complexity. Conversely, concrete structures have been observed to support a more varied range of trophic levels, which might be more akin to natural reefs (Brock and Norris 1989; Lemoine *et al.* 2019). Such findings underscore the need for careful consideration of AR design in achieving desired ecological outcomes.

Unexpected variations in community structures among natural reefs also emerged, suggesting inherent, natural differences in local reef ecosystems. This could be attributed to the unique biotic and abiotic characteristics of geographically isolated reefs, including the pinnacles that featured during the current study. A strong effect was also noted in another study in which the fish community was distinct depending on the species of coral which make up the reef (Komyakova *et al*. 2013). Therefore, the differences noted between artificial and natural reefs might reflect the natural heterogeneity of reef communities. If so, the observed disparities between reef types might not be as concerning as initially thought, warranting a more nuanced interpretation of their ecological impact.

Reef type habitat preferences

Results obtained from the SIMPER analyses suggest that despite the data having been transformed, dissimilarities found during PERMANOVA analyses may still have been strongly influenced by dominant species. This highlighted the importance of studying the species-specific habitat preferences in deepening our understanding of the performance of ARs in supporting fish communities. The preferences shown by all *Lutjanus* species towards ARs is particularly noteworthy as these fish are known to be of higher economic value (identified locally as having one of highest local values as described in Bauer *et al*. (2023) as well as being heavily targeted by regional fishing efforts (Pauly and Chuenpagdee 2003), and often susceptible to overfishing globally (Graham *et al*. 2008 Guardia *et al*. 2018; Souza *et al*. 2019). An early study of ARs used in the Gulf of Thailand, found that they attracted both *Lutjanidae* and *Serranidae*, in areas not normally found (Polovina 1991). Other studies have demonstrated that ARs often support mid-higher trophic level fish assemblages, including *Lutjanidae* and *Haemulidae* members (*e.g*. Arena *et al*. 2007; Dance *et al*. 2011; Paxton *et al*. 2020), similar to those of the current study. Reasons for this may be associated with the distinct morphological characteristics and vertical relief provided by ARs (Paxton *et al*. 2020; Harvey *et al*. 2021; Sensurat-Genc *et al*. 2022). Therefore, this may explain the apparent preferences of *Lutjanidae* and *Haemulidae* to ARs in the local region. ARs may therefore provide critical habitats to economically valuable species, which often occupy similar trophic levels, and face large fishing pressures. This key finding highlights the potential of ARs as valuable tools, effective in local fisheries management, specifically in providing refuge to targeted species, such as *Lutjanidae* members.

The observed preferences of certain fish towards natural reefs included a number of lower trophic members. This separation in habitat preferences amongst trophic levels suggests that while ARs might offer suitable habitats for mid-trophic species, they may not support lower trophic species as effectively as natural reefs. This may be due to their reduced habitat complexity, as well as their relatively low hard coral cover, compared to that of natural, healthy reefs. Corals are widely recognised as supporting lower trophic organisms through the provisioning of key habitats, refuge, and food sources (Bell and Galzin 1984; Coker *et al*. 2014; Layman and Allgeir 2020;). Previous studies have found close associations between coral diversity and overall coral cover with species richness and community structures of reef-associated fishes (Chabanet *et al*. 1997; Komyakova *et al*. 2013; Darling *et al*. 2017). This observation raises concerns as to the ability of recently deployed ARs to sustain similar levels of biodiversity compared to natural reefs, potentially highlighting their inability to promote ecosystems similar to those that exist on natural reefs. The findings from the current study, therefore highlight the importance of considering ecological characteristics, target species, and most importantly - deployment objectives, of future ARs used in the Gulf of Thailand.

Despite the observed dissimilarities in community structure between natural reefs and ARs, it is noteworthy that several species of differing ecological roles and trophic positions exhibited similar abundances across both reef types (*e.g. Chaetodon / Chelmon / Heniochus, Cheilinus*, *Carangoides, Epinephelus* >30cm and *Lethrinus*). This observation suggests that ARs, while distinct in certain aspects, can support a range of reef-associated fish, highlighting their potential positive impacts when used to provide habitats to reef fish, particularly where habitat degradation of natural reefs and overfishing are prominent. In addition to providing refuge and feeding grounds, ARs may also act as crucial fish recruitment sites, enhancing the production of fish populations (Seaman and Sprague 1991), as has been suggested in other areas (*e.g*. Cresson *et al*. 2014; Roa-Ureta *et al*. 2019). However, the much debated 'attraction/production hypothesis' as to whether artificial reefs simply attract fish from surrounding areas, or enhance the 'new' production of fisheries remains contested (Grossman *et al.* 1997; Smith *et al*. 2016; Mavraki *et al.* 2021). By offering alternative habitats, these artificial structures might alleviate pressure on natural reefs, contributing to a more balanced ecosystem. This may be especially pertinent in local regions where natural reefs are under significant anthropogenic stress.

Artificial Reef Design

The preferences of all *Lutjanidae* members to the HTMS Sattakut wreck suggests that shipwrecks may serve as crucial habitats to certain local species. Were this to be the case, it is likely that shipwrecks also provide important habitats to functional groups with similar ecological characteristics (*e.g. Haemulidae* and *Serranidae* – both of which are targeted by fishers due to their significant value (Bauer *et al*. 2023), and are reported to inhibit shipwrecks locally). Other studies have also found *Lutjanidae* members, as well as other mid- to higher- trophic fish families to be some of the most common inhabitants of shipwrecks (*e.g*. Branden *et al*. 1994; Workman and Watson 1995; Sreekanth *et al*. 2019, Medeiros *et al.* 2022), suggesting that shipwrecks may provide key habitats to mid-higher trophic species, often highly targeted by fishing efforts. Fish communities have been observed to differ in previous studies that compare metal and concrete structures (*e.g*. Paxton *et al.* 2020; Lemoine *et al*. 2019). Given the apparent local habitat preferences of several species observed living across different AR types, further species distribution and habitat selection within AR systems is likely to show significant design-related variation. Future studies that incorporate multiple designs of ARs will be key to identifying local AR species-specific associations.

Preferences demonstrated towards the concrete blocks by fish of more varied trophic positions may suggest these AR designs provide a better wide-scale solution to supporting a range of ecological roles. These findings suggest the significant importance of considering the ecological characteristics and preferences of target species when designing and deploying different types of ARs. Concrete ARs have demonstrated success in supporting fish assemblages (Brock and Norris 1989; Lemoine *et al*. 2019; Paxton 2020). Previous studies (*e.g*. Lemoine *et al*. 2019) have also suggested the closer mimicry of concrete ARs to the functioning of natural reefs, compared with steel ships. The observed differential attraction of species to various AR types not only has implications for enhancing fishery resources but also for local biodiversity conservation and ecosystem management. These insights, along with further studies could inform the strategic design of ARs to optimise their utility both as a tool for fisheries management and as a means to support and promote marine biodiversity. This aspect of AR performance is critical, as it points to the potential of tailored AR designs to cater to the habitat requirements of particular species or groups, thereby augmenting their effectiveness in achieving specific ecological and conservation goals.

The observed preferences of species to certain AR types, while suggestive of the influence of reef design and material on habitat suitability, may also be attributed to other factors (Komyakova *et al*. 2013). However, it is important to note that both AR types in this study were deployed at similar times, situated at similar depths, were of comparable sizes, and shared similar proximities to natural reefs. Moreover, these artificial structures were both located near isolated pinnacles that were alike in characteristics such as size, depth, and relative proximity to their AR neighbours. Such similarities between the locations of the ARs reduce the likelihood that these environmental factors solely accounted for the observed species preferences. Nonetheless, factors such as variations in site use, local fishing pressures, local current patterns or water quality as well as biological factors including local differences in substrate communities amongst ARs (as described by Monchanin *et al*. 2021), prey availability, or even temporal aspects (Carr and Hixon 1997; Sensurat-Genc *et al*. 2022) could play a role in determining species abundance and distribution, and should therefore be incorporated into future studies where possible. As a result, although our study suggests strong evidence for habitat preferences for a range of functional groups across AR types, it is important to acknowledge the limitations in the generalisation of these results.

Collectively, these results suggest a nuanced role of ARs used for conservation purposes associated with fisheries management. While they show promise as tools for supporting certain economically valuable species, their efficacy in maintaining broader ecosystem biodiversity appears limited, and that the support they provide to fish assemblages may be ecological role-specific. Both the observed differences in community structures, and fish habitat preferences may suggest that the benefits of ARs are highly specific to certain functional groups, or the ecological roles they occupy. Consequently, the conservation of natural reefs is likely to remain crucial for protecting the diversity, and functioning of reef ecosystems. This study therefore highlights the importance of a balanced approach to fisheries management, one that leverages the benefits of artificial structures, and their specific designs, while acknowledging and addressing their limitations in supporting high levels of marine biodiversity.

CONCLUSIONS

ARs show local dissimilarities in their community structures when compared with natural reefs, as well as when comparing different designs of ARs to one another. This study has provided valuable insights into the role of ARs, including shipwrecks, in the Gulf of Thailand's marine ecosystem, and their potential as tools for future fisheries management. Our findings highlight that ARs may serve as key habitats for species belonging to *Lutjanus*, *Epinephelus* etc. that are commonly targeted in commercial and recreational fisheries. However, the findings of this study also underscore the importance of continued research and strategic planning in the deployment of ARs, ensuring they are tailored to meet specific ecological and conservation objectives in the Gulf of Thailand, as well as the continued priority of coral reef conservation in the region whereby artificial reef environments do not provide habitat benefits for all functional groups, such as lower trophic species that are vital to trophic dynamics.

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APPENDIX A. Average fish population density per 1,200 m^2 (±SE) across all four study sites.

Fish (genus)	***Artificial*:** HTMS Sattakut wreck	***Natural*:** Hin Pee Wee	***Artificial*:** Artificial Reef Cubes	***Natural*:** No Name Pinnacle
Hipposcarus / Scarus / Chlorurus	4.41±0.49	5.71±0.74	11.40±2.02	7.61±0.84
Siganus	19.56±4.56	21.52±3.31	48.67±10.74	32.07±6.29
Chaetodon / Chelmon / Heniochus	10.04±1.12	10.24±0.75	10.73±1.39	13.38±1.20
Pomacanthus	0.76±0.24	1.11±0.18	1.14±0.23	1.62±0.19
Labroides	1.71±0.27	4.18±0.44	3.63±0.42	5.85±0.38
Platax	0.06±0.06	0.36±0.11	1.05±0.26	0.23±0.11
Hemigymnus	0.06±0.04	0.65±0.19	0.16±0.10	0.58±0.21
Cheilinus	2.57±0.34	2.60±0.47	1.16±0.36	1.92±0.34
Epibulus	0.00±0.00	0.11±0.09	0.09±0.09	0.16±0.13
Diagramma / Plectorhinchus	6.10±0.91	1.03±0.27	4.60±1.40	0.23±0.11
Myripristis / Sargocentron	0.41±0.29	1.27±0.36	0.00±0.00	0.00±0.00
Balistoides	0.62±0.16	0.54±0.11	1.34±0.25	0.79±0.10
Diodon	0.06±0.06	0.04±0.03	0.19±0.10	0.05±0.04
Taeniura / Pateobatis	0.00±0.00	0.01±0.01	0.14±0.07	0.00±0.00
Lutjanus	117.15±10.29	11.14±2.00	18.36±2.66	0.41±0.15
Gymnothorax	0.00±0.00	0.03±0.02	0.00±0.00	0.05±0.04
Carangoides	2.63±1.19	2.31±0.79	9.42±6.13	1.42±0.44
Lethrinus	5.03±1.83	11.84±2.98	4.40±0.99	3.05±0.59
Plectropomus / Epinephelus <30cm	3.23±0.39	26.36±1.97	13.57±2.55	26.83±2.64
Epinephelus >30cm	4.50±0.70	2.28±0.43	4.35±0.48	5.55±0.96
Sphyraena	0.88±0.60	80.83±15.70	67.84±19.24	0.00±0.00

APPENDIX B. Median fish population density per 1,200 m^2 for each reef type.

Fish (genus)	Natural reef (median)	Artificial reef (median)
Lutjanus	2.17	84.75
Diagramma / Plectorhinchus	0.17	4.00
Labroides	5.00	2.50
Hemigymnus	0.25	0.00
Cephalopholis / *Epinephelus* <30cm	24.50	4.25
Pomacanthus	1.25	0.75

APPENDIX C. Median fish population density per 1,200 m^2 for each artificial reef site.

Fish (genus)	HTMS Sattakut (median)	Artificial Reef Cubes (median)
Lutjanus	176.00	21.25
Cheilinus	2.50	0.71
Hipposcarus /Scarus /Chlorurus	4.50	10.00
Siganus	16.00	38.28
Labroides	1.75	4.00
Balistoides	0.50	1.42
Sphyraena	0.00	43.75
Platax	0.00	0.88
Cephalopholis / *Epinephelus* <30cm	3.50	12.38

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