

**Distribution, abundance, diversity and habitat associations of fishes  
across a bioregion experiencing rapid coastal development**

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*Running Head: Fish-habitat associations across north-western Australia*

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additive mixed models; habitat; spatial distribution; biodiversity

## 27    **ABSTRACT**

28    Knowledge of the factors that influence spatial patterns in fish abundance, distribution  
29    and diversity are essential for informing fisheries and conservation management. The  
30    present study was conducted in the nearshore Pilbara bioregion of north-western  
31    Australia where the dynamic marine environment is characterised by large embayments,  
32    numerous islands and islets, coexisting with globally significant petrochemical and  
33    mineral industries. Within Western Australia, this nearshore bioregion has high  
34    biodiversity and is considered to play an essential role in the recruitment of species of  
35    commercial importance. To better inform future investigations into both ecological  
36    processes and planning scenarios for management, a rapid assessment of the  
37    distribution, abundance and associations with nearshore habitats of fishes across the  
38    region was conducted. Baited remote underwater stereo-video systems (stereo-BRUVs)  
39    were used to simultaneously sample the fish assemblage and habitat composition.  
40    Generalised additive mixed models (GAMMs) were used to determine whether the  
41    abundance of fishes were related to habitat and a range of environmental variables  
42    (visibility, depth, distance to 30 m and 200 m depth isobars, boat ramps and the nearest  
43    large embayment (Exmouth Gulf). A diverse fish assemblage comprising 343 species  
44    from 58 families was recorded. The abundance and distribution patterns of fishery-  
45    target species and of the five most common and abundant species and families were  
46    linked positively with areas of high relief, hard coral cover, reef and macroalgae and  
47    negatively with the distance to the nearest oceanic waters (200 m depth isobar). This  
48    study provides information that can contribute to future marine spatial planning  
49    scenarios for management of the Pilbara using a unique, analytical approach that has  
50    broad application in biogeography.

## 1. Introduction

Information on relationships between fish and habitats is essential for understanding the processes driving patterns of fish diversity and abundance. Habitat type and complexity are important determinants of the structure of fish assemblages (Friedlander and Parish, 1998; Almany, 2004; Travers et al., 2006; 2010; 2012; Giakoumi and Kokkoris, 2013; Wakefield et al., 2013). Fish abundance, diversity and distribution has been shown to be positively correlated with the structural complexity of habitats, likely due to the additional refuge from predators and availability of resources (e.g. food) that complex habitats offer (Newman and Williams, 1996; 2001; Newman et al., 1997; Friedlander et al., 2003; Willis and Anderson, 2003; Wilson et al., 2012). Understanding these relationships and natural patterns in fish abundance and diversity enables natural and anthropogenic impacts to be assessed. Knowledge of the spatial distribution of habitats and their relationship with fish is therefore essential for informing fisheries management and conservation (Curley et al., 2002).

The Pilbara region hosts fish assemblages characterised by high diversity and economically important, but low productivity, fisheries (MPRSWG, 1994; Fox and Beckley, 2005; Molony et al., 2011; Newman et al. 2014). In addition, rapid coastal development has been occurring at multiple locations throughout the region to support the mineral and petrochemical industries (PDC, 2015). This development has the potential to directly impact the biodiversity and productivity of vulnerable nearshore ecosystems via dredging, construction, pollution, shipping and other indirect pressures associated with increased human populations (e.g. fishing) (Pandolfi et al., 2003; Crain

et al., 2009; Waycott et al., 2009). Management is challenged with finding a balance between the economic benefits of non-renewables, sustainable fisheries development and maintenance of biodiversity and ecosystem services. Knowledge of the patterns and processes that support productivity biodiversity of these nearshore marine ecosystems is therefore essential for informing management decisions (Parsons et al., 2014).

Nearshore marine habitats in the Pilbara, including macrophyte and sessile invertebrate assemblages, are likely to be vulnerable to coastal development pressures, with these habitats considered to be essential for the recruitment of important fishery species. In this region, recruits and juveniles of important commercial and recreational fishery species are thought to be spatially partitioned from adult populations and associated with different habitats (Evans et al., 2014). Knowledge of fish-habitat relationships across the Pilbara is lacking, but is required for the identification of priority areas for the recruitment of target fish species, areas of high biodiversity and vulnerable habitats. Such information would inform research into how these important areas may be affected by ongoing coastal development associated with the petrochemical and mineral industries.

Buoyed by the construction and operation of major coastal development projects in the Pilbara, levels of boat-based recreational activity peaked in 2012/13 (Fletcher and Santoro, 2014; Ryan et al., 2013; 2015). There is a seasonal peak in angling activity during the winter months when local populations are inflated by significant numbers of metropolitan and inter-state tourists in addition to the contribution from the workforce associated with construction or operation of major developments in the region (Fletcher

and Santoro, 2014). Owing to the large tidal range in the Pilbara, nearshore recreational angling activity is mainly boat based for a variety of finfish species including barramundi (*Lates calcarifer*), mangrove jack (*Lutjanus argentimaculatus*), trevallies (Carangidae) and groupers (Epinephelidae) in nearshore waters. Tropical snappers (Lutjanidae), emperors (Lethrinidae), groupers (Epinephelidae), trevallies (Carangidae), tuskfish (*Choerodon* spp.) and mackerels (Scombridae) are also targeted further from shore (Fletcher and Santoro, 2014). The two main commercial fisheries operating within nearshore Pilbara waters are the Onslow and Nickol Bay prawn trawl fisheries that predominantly target banana prawns (*Penaeus merguensis*) and the mackerel managed fishery that predominantly targets Spanish mackerel (*Scomberomorus commerson*) (Fletcher and Santoro, 2014). Commercial fisheries (fish trap, fish trawl and line) operate in continental shelf waters (30-500 m).

The current study is the first contribution from a five-year project aiming to create ecological models for use by management agencies assessing the impacts of coastal development associated with petrochemical and mineral extraction industries on biodiversity values and fisheries productivity in the Pilbara. As part of this integrated study, a novel application of a standardised benthic classification system was adopted to simultaneously collect semi-quantitative measures of habitat from an established fish survey method, baited remote underwater stereo-video (stereo-BRUV). These data were subjected to multivariate analyses to investigate ecological processes underlying the distribution, abundance and diversity of fishes along the extensive coastline of the Pilbara bioregion through the following hypotheses: (1) The relative abundance and diversity (species richness) of fishes are greatest in more structurally complex habitat

types such as hard and soft corals, (2) The relative abundance and diversity of fishes will be greatest closer to large embayments where fish nursery habitats occur, (3) The relative abundance and diversity of fishes will be greatest in areas furthest from boat ramp access where fishing pressure may be least. Emphasis will be placed on identifying areas of notable abundance and diversity and the species and family groups mainly responsible for the observed patterns along the length of the Pilbara coastline.

## **2. Materials and Methods**

### *Study site*

This study took place in the western Pilbara region of Western Australia spanning a distance of approximately 340 km from the eastern end of the Exmouth Gulf in the south (114° 8' 55.47E, 21° 55' 19.15S) to the Dampier Archipelago in the north (116° 56' 12.945E, 20° 24' 19.94S; Figure 1). The marine environment is tropical with a component of sub-tropical species, which are more prominent in the assemblage towards higher latitudes (Hutchins, 2001).

### *Sampling protocol and equipment*

Surveys were conducted over a ten day period in May, 2014 using baited remote underwater stereo-video systems (stereo-BRUVs; Video 1). A total of 212 deployments were conducted in 6-21 m depth (mean  $9.7 \pm 0.1$  m) across a range of habitat types, in areas open to recreational and charter fishing. Stereo-BRUVs were deployed on reefs or areas in close proximity to reefs with seabed structure present, *i.e.* we attempted to minimise large expanses of sand and as such these habitats are likely underrepresented in this study.

Ten stereo-BRUVs were used concurrently to maximise sampling efficiency. These systems comprised a pair of high definition video cameras, either Canon Legria HFG25 or GoPro Hero3+ (silver and black models) set to record at 25 and 60 frames per second, respectively. The cameras are inwardly converged at 7° to provide an overlapping field of view and are fixed to a galvanised steel bar within a trapezium-shaped frame (see Langlois et al., 2010; Watson et al., 2010; see Video 1). Further information on the design configuration and calibration of these stereo-BRUVs can be found in Harvey and Shortis (1996, 1998). To maximise calibration stability, the systems used a purpose-built, dual housing mounted on a base bar with a design that minimises camera movement within the housing, and between the cameras.

Each stereo-BRUV was baited with approximately ~1 kg of pilchards (*Sardinops* spp.) contained within a plastic-coated wire mesh basket, attached to a conduit rod and positioned 1.2 m in front of the cameras. Bait was crushed to promote dispersal of the flesh and fish oil. Each system was deployed by boat and left to film remotely for at least 60 minutes on the seafloor before being retrieved and re-deployed. Neighbouring deployments were separated by at least 400 m to reduce the likelihood of fish swimming between stereo-BRUVs (see Cappo et al., 2004).

## *Video Analysis*

### Fish assemblages

All fish were identified to species where possible, however several species could not be reliably or consistently identified to species level from video images. These included

various species of mackerel (herein referred to as *Scomberomorus* spp.), threadfin  
bream (*Nemipterus* spp.), flounder (*Bothidae* spp.), flathead (*Platycephalus* spp.),  
whiting (*Sillago* spp.) and two species of coral trout (*Plectropomus leopardus*,  
*Plectropomus maculatus*). The majority of trout species in the Pilbara region are likely  
to be *P. maculatus*, but *P. leopardus* also occurs and they cannot consistently be  
differentiated on video. Here, these important target species are considered together as  
*Plectropomus* spp. When juvenile lethrinids and scarids (individuals <12 cm) could not  
be identified to species level, they were recorded as *Lethrinus* spp. and *Scarus* spp. (see  
Supplementary Data S-Table 1).

Stereo-BRUVs were calibrated using the software CAL and subsequent analysis of  
videos was facilitated through the program EventMeasure (<http://www.seagis.com.au>).  
Relative abundance counts were obtained as the maximum number of fish belonging to  
each species, present in the field of view of the stereo-BRUVs at one time (MaxN;  
Priede et al., 1994; Cappo et al., 2004). Measures of species richness were obtained as  
the total number of species observed on each stereo-BRUV deployment. While the  
stereo-configuration of the video systems allowed us to obtain accurate and precise  
measurements of fish length using EventMeasure, this data is not reported here.  
However, the stereo-enabled capacity to measure distance was used to finalise measures  
of relative abundance by confirming whether each individual comprising MaxN was  
within our sample boundary of 10 m. Data checking and formatting of EventMeasure  
MaxN outputs were undertaken using scripts provided in Langlois et al., (2015) using  
the R language for statistical computing (R Development Core Team, 2015).



Five target species were selected from the dataset for focussed analysis with these species being the most common and/or were of significant importance to recreational and commercial fisheries. The selected species were: *Choerodon schoenleinii* (blackspot tuskfish), *Epinephelus multinotatus* (rankin cod), *Lethrinus nebulosus* (spangled emperor), *Lutjanus carponotatus* (stripey snapper) and *Plectropomus* spp. (coral trout). *E. multinotatus* were not analysed in statistical models, however, due to low abundance. In addition, we focussed analyses on the five most commonly observed (% of deployments) fish families and on the five most common fish species.

#### Habitat variables

Measures of habitat and relief were obtained from the stereo-video imagery using the software program TransectMeasure (<http://www.seagis.com.au>). This method of analysis used a 5 x 4 grid which was overlaid on a high definition image obtained from each stereo-BRUV deployment. Within each grid rectangle, the dominant habitat type was characterised using a novel application of the CATAMI classification scheme (Althaus et al. 2013; Harrison et al., 2014; Hill et al., 2014), with some modification to simplify naming schemes. This resulted in the selection of eight broad habitat types: 1) hard corals, 2) macroalgae, 3) reef (boulders or pavement – including those covered in turfing algae + hard corals + macroalgae), 4) sand/rubble, 5) seagrass, 6) soft corals, 7) sponges and, 8) ascidians. For every deployment we had a list of all habitat types and a corresponding number of grid cells in which it was present. For simplicity we refer to the data as ‘percent cover’ for each habitat type but effectively it is how often each were encountered. When grid rectangles were positioned over open water they were classed as ‘no biota’ and excluded from the overall percent cover and final statistical analyses.

In cells where biota was present, estimates of relief were also obtained and ranked as flat (no relief), low (<1 m), medium (1-3 m) and high (>3 m) with an average and standard deviation calculated for each deployment.

#### Environmental variables

The depth (m) and the GPS latitude and longitude position was recorded at the time of each deployment. Rather than examining the relationship between latitude and longitude with fish and habitats, we used positional measures that we considered were most applicable to the marine environment in the western Pilbara region. The first two positional variables were the minimum distance of each stereo-BRUV deployment to the 30 m and 200 m depth isobars. At the northern end of the Pilbara the 200 m depth isobar is approximately 160 km offshore and the marine environment is quite sheltered from the open ocean, while at the southern end the 200 m depth isobar is approximately 15 km offshore and the water is clearer and more readily flushed by oceanic waters. The third positional predictor variable included in analyses was ‘distance to the Exmouth Gulf’, a large shallow embayment approximately 3000 km<sup>2</sup> in area located to the southwest of the Pilbara region. This Gulf’s nearshore waters on the eastern and south-western side are important fish nursery areas (MPRSWG, 1994) and therefore a potentially important source of juveniles to the south-western Pilbara region. Lastly, the fourth positional predictor variable included was minimum distance to the nearest boat ramp. There are six boat ramps between Exmouth Gulf and Dampier in the remote Pilbara region. Finally, visibility was recorded as a proxy for turbidity with estimates made by the same experienced analyst for every stereo-BRUV deployment.

243 *Data analysis*

244 The influence of habitat and environmental variables on the abundance of fish was  
245 investigated using generalised additive mixed models (GAMMs; Lin and Zhang, 1999).  
246 GAMMs are an extension of generalised additive models (GAMs; Hastie and  
247 Tibshirani, 1986) which use a sum of smooth functions to model covariate effects – as  
248 opposed to a linear (or some other parametric) form. This allows for more flexible  
249 functional dependence of the response variable on the covariates, making GAMs (and  
250 GAMMs) useful for capturing the shape of a relationship without making prior  
251 assumptions about its parametric form. To accommodate for overdispersion and  
252 correlation in the data, which arise in many fields of research (e.g. longitudinal studies,  
253 Lin and Zhang, 1999), we extend the application of this class of models by including  
254 replicates as a random effect (Harrison, 2014).

255  
256 Model selection was based on Akaike Information Criterion (AIC; Akaike, 1973) and  
257 AIC weights (wAIC; Burnham and Anderson, 2002). A full subsets method was used to  
258 fit models of all possible combinations up to a maximum of three variables – to prevent  
259 overfitting. Models containing variables with correlations  $> 0.4$  were also excluded  
260 from the analysis to eliminate strong collinearity, which can cause problems with over-  
261 fitting and make interpretation of statistical results difficult. Models with AIC values  
262 that differ by less than two units show weak evidence for favouring one over the other  
263 (Raftery, 1995; Burnham and Anderson, 2002). The best model was therefore the one  
264 with the fewest variables (most parsimonious) and was within two AIC units of the  
265 lowest AIC value (Burnham and Anderson, 2002). The wAIC, which represents  
266 probabilities or weights of evidence for each model, were used to facilitate

interpretation of the best models. Relative support for each predictor variable was obtained by calculating the summed wAIC across all subsets of models containing that variable to obtain its relative importance (Burnham and Anderson, 2002). For these variable importance metrics to be meaningful, it is necessary to have the same number of models containing each variable (Burnham and Anderson, 2002). As this was not the case due to removal of models with highly collinear predictor variables, we calculated per model averaged variables weights (average wAIC) by dividing each weight (wAIC) by the total number of models containing each variable or class of variables, respectively. These were then rescaled to between 0 and 1 (with 1 being the variable with the highest relative weight). The large differences in the overall fit of the models meant these rescaled variable importance values were multiplied by the  $R^2$  value of the best model for plotting. This ensured that the overall importance of each variable was presented in the context of explanatory power.

Prior to analyses, three habitat categories (seagrass, sponges, and ascidians) were removed due to their limited coverage. A fourth category, sand/rubble, was also excluded due to strong collinearity with the category reef. Several variables (depth, soft corals, and hard corals) were  $\log_{10}(x+1)$  transformed to downplay outlying values and better represent relationships with fish abundance. Since GAMMs can account for data that are not normally distributed, models were fitted to untransformed fish abundance data using a Poisson distribution but allowing for overdispersion with the addition of an observation level random effect. All analyses were performed using the R language for statistical computing (R Development Core Team, 2015) with the package GAMM4 version 0.2-3 for GAMMs (Wood and Scheipl, 2015).

### 3. Results

#### *Patterns in the distribution and abundance of fish*

The 212 stereo-BRUV deployments analysed from the nearshore Pilbara region yielded at least 31171 individuals (sum MaxN's) from 343 species and 58 families (Supplementary Data S-Table 1). Examples of the fish assemblages encountered are shown in a short video clip (Video 1). Several protected species (Fish Resources Management Regulation 1995) were observed during the study. These included four *Epinephelus tukula* (potato cod; 946 – 1377 mm fork length) on separate deployments at the Muiron Islands, one 1500 mm *Epinephelus lanceolatus* (Queensland groper) at Legendre Island, Dampier and one *Pristis zijsron* (green sawfish) near Thevenard Island. The sawfish measured 4345 mm in length from rostra tip to tail fork, with a rostra length of 1390 mm (Video 1 at 1:30 minutes). The five most ubiquitous fish species observed were: *Scolopsis monogramma* (rainbow monocle bream; 67% of deployments), *Scomberomorus* spp. (mackerel; 62%), *Choerodon cauteroma* (blue-spotted tuskfish; 58%), *Carangoides fulvoguttatus* (gold-spotted trevally; 56%) and *Pentapodus porosus* (northwest threadfin bream; 51%) (Figure 3). The most ubiquitous families were: Nemipteridae (threadfin bream; 93% of deployments), Labridae (wrasses and tuskfish; 90%), Lethrinidae (emperors; 81%), Carangidae (trevallies; 80%) and Epinephelidae (groupers and coral cods; 76%) (Figure 4).

Patterns in the relative abundance of common species, target species and families were remarkably similar across the western Pilbara region (Figures 2-4). The majority of target species and common species peaked in mean relative abundance in the vicinity of

the Serrurier, Bessieres and Thevenard Islands (*C. schoenleinii*, *E. multinotatus*, *L. nebulosus*, *Plectropomus* spp. Figure 2; *C. fulvoguttatus*, *P. porosus*, *S. monogramma*, *Scomberomorus* spp. Figure 3). This peak in relative abundance around these islands was also reflected in species richness data (Figure 2) and at the family level, with the exception of Lethrinidae (Figure 4). High abundances were also recorded in the north between Cape Preston and Dampier. In this location there were high abundances of *L. carponotatus*, *Plectropomus* spp. (Figure 2), *C. cauteroma* and *S. monogramma* (Figure 3). Lethrinids were also particularly abundant between Cape Preston and Dampier, with this pattern not driven by *L. nebulosus* but by other species including *L. atkinsoni* and *L. punctulatus*. The fewest species, and lowest relative abundance measures of common species, target species and families were observed on deployments conducted in the nearshore region between the Mangrove Islands and Long Island (Figures 2-4).

#### *Habitat distribution*

The distribution of structurally complex habitats across the western Pilbara matched closely to areas of peak abundance for fish (Figure 5). The percent cover of hard coral was greatest at the northern tip of the northwest Cape whilst the percent cover of reef was more uniformly distributed across the region (Figure 5). Soft corals were observed to exhibit higher cover rates at the offshore Islands south of and including Thevenard Island and in the Dampier Archipelago, a pattern also exhibited by macroalgae (Figure 5). Percent cover of macroalgae was also high at Islands to the north of Thevenard. Deployments conducted between the Mangrove Islands and Long Island generally had the lowest relief and percent cover of hard corals, soft corals, macroalgae and reef, matching the lowest abundances of common and target fish species.

### *Importance of environmental and habitat variables for fish*

The best-fitted models utilising environmental and habitat variables were generated for species richness and the total abundance of fish in the Pilbara (Table 1). The variable importance plot (Figure 6) illustrates the strength of these variables in relation to those obtained in the top models for species and families. Positive relationships were obtained between species richness and the percent cover of reef and hard coral (Figure 7). Total abundances of fish were also greater in areas of higher hard coral cover (Figure 7). Species richness tended to decline with increasing distance to the 30 m depth isobar and similarly total abundance tended to be greater where the distance to the 30 m depth isobar was <100 km. Total abundance was also greatest closest to Exmouth Gulf and declined with increasing distance from the Gulf (Figure 7).

Despite similar relative abundance distributions of each of the target species across the Pilbara, a variety of different variables were important for these species (Table 1; Figure 6). For *C. schoenleinii* the top model included a single variable, macroalgae, but the importance of this variable for influencing the relative abundance of this species was weak (Table 1; Figures 6), with only a slight positive relationship between percent cover of macroalgae and abundance (Figure 7). The relative abundance of *L. nebulosus* declined with the declining cover of soft corals and with increasing distance to the 200 m depth isobar (Figure 7). The top model for *L. carponotatus* was not strong (Table 1; Figure 6) but suggested that the percent cover of macroalgae, SD relief and depth were each, to a small degree, influencing the abundance of this species. *L. carponotatus* were most abundant where macroalgae cover was either <40% or >80%, where SD relief was

high (indicating variable relief) and where depths were the shallowest. Of the target species, the strongest model was obtained for *Plectropomus* spp. (Table 1) with it being most abundant in areas with the greatest percent cover of reef (Figures 2, 4, 7).

Increasing visibility was weakly related to greater abundances of *C. fulvoguttatus* (Figure 8), however the model strength was low (Table 1) and the variable relatively unimportant (Figure 6). Distance to the 30 m depth isobar and distance to the Exmouth Gulf were both important variables for the relative abundance of *C. cauteroma* (Table 1; Figure 6). This species was most abundant at mid-distances (20-40 km) from the 30 m depth isobar and increased in abundance with increasing distance from the Exmouth Gulf (Figure 8). Model strength for *P. porosus* was quite high (Table 1) with the relative abundance of this species having a strong negative relationship with relief (Figure 8). There was also a weak positive relationship between abundance and macroalgae cover and a bimodal pattern in abundance with distance to the 30 m depth isobar with higher abundances at distances closest to, and farthest away from this depth contour. *S. monogramma*, the most common fish species observed in the Pilbara, like *C. cauteroma* tended to increase in abundance with increasing distance from the Exmouth Gulf (Figure 8). A weak negative relationship was observed with *S. monogramma* and the cover of macroalgae and distance to the 30 m depth isobar. Lastly, the top model for *Scomberomorus* spp. contained a single variable, reef (Table 1), with the highest cover of reef corresponding to lowest abundances for this species (Figure 8).

The percent cover of reef was present in most of the top models for families (Table 1; Figure 6). Increasing cover of reef was associated with increasing abundances of



Labridae, Lethrinidae and Epinephelidae (Figure 9). Distance to the 30 m depth contour was also an important variable in the top models for Lethrinidae, Nemipteridae and Epinephelidae (Table 1) with each group exhibiting a weak negative relationship between abundance and distance to this depth contour (Figure 9). For Labridae, additional important variables included distance to the 200 m depth isobar which had a bimodal relationship with abundance (lowest at mid distances), and the percent cover of soft corals which had a positive relationship with abundance (Figure 9). Important variables for Nemipteridae mirrored those obtained for the most common species of this group, *P. porosus*. Lastly, in addition to reef and distance to the 30 m depth contour, Epinephelidae abundance was greater in areas of high coral cover (Figure 9).

#### 4. Discussion

The diverse ichthyofauna in shallow nearshore waters (i.e. < 22 m) of the Pilbara region of northwest Australia compares favourably to levels of diversity surveyed in the Kimberley region, approximately 800 km to the north of Dampier (Cappo et al. 2011). Cappo et al. (2011) conducted 154 BRUV deployments in nearshore (<20 m) habitats across ~30 km of coastline, recording 7108 individuals from 116 species. This is markedly less than the 31171 individuals from 343 species recorded from 220 stereo-BRUV deployments conducted along the ~340 km nearshore stretch between Dampier and the Exmouth Gulf (Figure 1). The disparity is likely primarily due to habitat differences, with those sampled in the Kimberley region being more 'sandy', with low rugosity and a lack of sub-tidal coral reefs (Cappo et al. 2011). Numbers of individuals and species observed in the present study were, however, very similar to those recorded from 1100 BRUV deployments conducted across more than 2000 km of lagoonal and

inter-reef waters of the Great Barrier Reef Marine Park of the north-east coast of Australia (39,989 individuals from 347 species; Cappo et al. 2007). These results suggest that the Pilbara region is similar to other sub-tropical and tropical regions around Australia, with fish assemblages characterised by high levels of diversity. This high diversity is likely to be an ecological response to the limited productivity and nutrient deprived marine environments of Western Australia (Molony et al. 2011).

Islands in the south of the Pilbara, including North and South Muiron, Serrurier, Bessieres, Thevenard and Airlie Islands (Figure 1), possessed the most species-rich assemblages and highest relative abundances of fish, including important fishery-target species and protected species. Around these islands, structurally complex reef systems were present with a high coverage of hard corals, macroalgae and soft corals. Here, the distance to the 30 m and 200 m depth isobars is at a minimum for the region, likely representing increasing exposure to more oceanic water conditions compared to areas further north in the Pilbara. A similar finding was reported by Sandin et al., (2008) who showed that the diversity of Caribbean reef fish increased with increasing connectivity and nearshore productivity and declined with isolation. In the southern Pilbara, a closer proximity to oceanic waters appears to be an important positive driver of high fish diversity (Hutchins et al., 1996; Hutchins, 2001).

Whilst coastal coral reefs of the Pilbara are adapted to high levels of natural disturbance (cyclones, tidal currents; Gilmour et al., 2006), corals can be vulnerable to additional anthropogenic disturbances due to limited demographic and genetic replenishment (Underwood et al., 2013). That is, they rely on their own genetic diversity to adapt to

environmental change. In this study, strong links were identified between coral cover and fish diversity and abundance at the small offshore islands in the southern Pilbara. Extreme climatic events such as the heat wave that occurred in 2010/2011, combined with pressures associated with significant coastal development supporting the petrochemical and mineral industries, e.g. increased sedimentation, turbidity, and salinity (Gilmour et al., 2006), potentially threaten coral communities, and other sensitive habitats (e.g. benthic primary producers), throughout the Pilbara. Across the globe, a range of anthropogenic (e.g. climate change, overfishing, habitat destruction and pollution) and natural disturbances act in tandem over time to threaten the resilience of habitats and fish communities (Jackson et al., 2001; Bornt et al. 2015; van der Veer et al., 2015). A meta-analysis by Wilson et al., (2006) showed strong links between fish and corals with coral loss (e.g. severe tropical storms) having a greater impact on fishes than coral disturbance (e.g. bleaching). To assist conservation management for the Pilbara, further research into the ecological processes supporting these diverse island communities and the threats to them is warranted.

Bordering the southern Pilbara is Exmouth Gulf, a large, shallow embayment where there is a paucity of information on fish assemblages (Figure 1). A single study, conducted by Hutchins et al. (1996) documented the presence of fish species along the eastern margins of the Gulf. Exmouth Gulf is a known source of nutrients that support a significant commercial prawn trawl fishery with extensive mangroves and seagrass beds (McCook et al., 1995). Like marine embayments elsewhere in Western Australia (Wakefield et al., 2011) and in other parts of the world (Berkström et al., 2013), the Exmouth Gulf likely provides important nursery habitats for fish. The small offshore

islands in the south of the Pilbara, in relatively close proximity to the Gulf, were the only locations where juvenile ( $< 120$  mm) lethrinids and scarids, too small to identify to species (Supplementary Data S-Table 1) were recorded. However, with sampling in shallower depths we would expect to also see juveniles where the cover of macroalgae and soft corals was greatest, i.e. between Cape Preston and Dampier in the north with such habitats likely important habitats for juvenile fish (Wilson et al., 2010; Evans et al., 2014). Exmouth Gulf is likely to be a source of nutrients, from the minimal land run-off, and a potential area of juvenile recruitment due to the shallow macrophyte assemblages (McCook et al., 1995). Given these factors and the paucity of information on Exmouth Gulf, the influence of this significant embayment on the whole Pilbara region requires further investigation.

It is generally accepted that fish populations around human population centres will be very different to those on isolated reefs (Stevenson et al. 2007; Williams et al. 2011; Edgar et al. 2014). Along these lines, boat ramp access points within the Pilbara are typically co-located with major human coastal populations and we hypothesised that fish populations furthest from access points would have the greatest abundance of target species (see also Langlois et al., 2012). However, the distance to boat ramp variable was not present in any of the top models and therefore was not found to have a driving influence on the abundance of target fish species. Fish abundance and species richness at the islands in the southern Pilbara were greater than those sampled in more remote locations within the region with no relationship evident with distance to boat ramps.

The lowest species richness and relative abundances of key species groups were observed on deployments conducted between the Mangrove Islands and Long Island (see Figure 1). Whilst we targeted nearshore reef habitats, in these locations reefs were covered in macroalgae and silty sediment with very little hard coral cover. Here, distances to the 30 and 200 m depth isobars are at a maximum, likely limiting any oceanic flushing through this nearshore region. These habitat and environmental patterns closely match the relative abundances of target and common fish species as indicated in the spatial plots (Figures 2-4) and residual abundance plots (Figures 7-9). This distinct mid-region area was well represented in many of the residual abundance plots and is characterised by a bimodal pattern indicating lower abundance and diversity (Figures 7-9). Coastal habitats inshore of sites sampled in this region are characterised by expansive mangroves crossed by tidal creeks and fronted by intertidal mudflats (Heyward et al., 2006; Human and McDonald, 2009). Sediments are likely transported from these coastal areas to the offshore reefs via tidal movements. These nearshore sandy areas in the Pilbara region are notoriously difficult to sample using visual techniques due to high turbidity and very limited visibility. As we avoided sampling bare sandy habitats, there is an underrepresentation of sand-affiliated species in our data (see Supplementary Data S-Table 1). For example, Travers et al., (2010, 2012) recorded high abundances of Synodontidae (lizardfishes) and Monacanthidae (leatherjackets) in soft sediments in the Pilbara, both of which were observed in very low abundances in the current study.

The nearshore marine environment in the northern Pilbara between Cape Preston and Dampier appears to be an important region for coral trout (*Plectropomus* spp.) and

lethrinids (Figure 2-4). For lethrinids, this reflects greater abundances of particularly the blue-spotted emperor (*L. punctulatus*, Figure 2). *L. punctulatus*, a north-western Australian endemic species, is perhaps at the centre of its distribution here, with adjacent cross-shelf areas having the highest levels of abundance in commercial catches (Newman et al. 2014). This may also explain why the area to the east along the Canning Coast, which lacks these offshore islands and associated habitats, does not appear to exhibit similar levels of abundance for this species. It thus appears that this species likely exhibits life history partitioning between juveniles and adults, with specific habitat associations for juveniles limiting their abundance and distribution along this coastline, despite exhibiting highly productive life history characteristics (e.g. early maturation, protracted spawning period, short lifespan, Wakefield pers. comm.). This situation may also apply to other species with limited distributions (i.e. endemics). Further investigation of the role of these nearshore habitats for juvenile emperor and their links with offshore commercial fisheries in the region is required.

This study is the first example where a standardised habitat classification scheme (CATAMI, Althaus et al. 2013) has been applied to rapidly quantify habitat cover and relief derived from forward facing stereo-BRUVs. Classification of imagery from stereo-BRUVs has previously been demonstrated to be an adequate proxy for hydro-acoustic derived habitat maps for predicting fish habitat suitability (Monk et al., 2011). Here, the simultaneous video sampling of fish and habitats has provided a useful benchmark of the abundance and distribution of fish and fish-habitat relationships across the nearshore Pilbara region of north-western Australia. While the use of bait enables an enhanced survey of a greater abundance and diversity of fish species, the

attraction of fish from surrounding areas may limit inferences about fish-habitat relationships, particularly where habitats are patchily distributed. This study also harnesses modern statistical methods to examine the functional trend between variables and a broad range of predictors, assessing whether a trend is evident and if so, what is the form or shape (linear or nonlinear). By combining the use of a standardised habitat classification schemes with GAMMs and full-subsets analyses, a powerful analytical approach for gathering knowledge has been developed that has broad application in biogeography.

#### **ETHICS STATEMENT**

Sampling was conducted in waters off north-western Australia and was covered by The University of Western Australia Animal Ethics Approval # RA/3/100/1317.

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**Table 1.** Best generalized additive mixed models (GAMMs) for predicting the abundance of fish in the Pilbara, i.e. those within two units of the lowest Akaike Information Criterion (AIC) value, which have the fewest variables.

	Dependent variable	df	R <sup>2</sup>	AIC	BIC	wAIC	Best model
	Total Abundance	10.39	0.43	2487.91	2504.69	0.78	Hard corals, Distance to 30 m, Distance to Gulf
	Species Richness	6.53	0.57	1600.45	1617.23	0.99	Hard corals, Reef, Distance to 30 m
Family	Carangidae	–	0	1532.54	1539.19	0.05	Null
	Epinephelidae	6.72	0.20	977.11	993.89	0.24	Soft corals, Reef, Distance to 30 m
	Labridae (Labrinae)	9.54	0.29	1484.35	1501.13	0.76	Soft corals, Reef, Distance to 200 m
	Lethrinidae	6.17	0.11	1315.33	1328.76	0.08	Reef, Distance to 30 m
	Nemipteridae	8.40	0.17	1311.55	1328.34	0.51	Relief, Macroalgae, Distance to 30 m
Common Species	<i>C. fulvoguttatus</i>	3.70	0.04	836.33	846.40	0.04	Visibility
	<i>C. cauteroma</i>	5.92	0.24	580.33	593.76	0.12	Distance to 30 m, Distance to Gulf
	<i>P. porosus</i>	9.61	0.20	992.99	1009.78	0.66	Relief, Macroalgae, Distance to 30 m
	<i>S. monogramma</i>	8.61	0.25	582.47	599.26	0.58	Macroalgae, Distance to 30 m, Distance to Gulf
	<i>Scomberomorus</i> spp.	3.07	0.16	531.35	541.42	0.06	Reef
Target Species	<i>C. schoeleinii</i>	2.93	0.07	456.57	466.64	0.04	Macroalgae
	<i>L. nebulosus</i>	9.29	0.11	642.38	655.81	0.09	Soft corals, Distance to 200 m
	<i>L. carponotatus</i>	15.04	0.08	495.01	511.79	0.36	Depth, SD Relief, Macroalgae
	<i>Plectropomus</i> spp.	5.96	0.17	553.03	566.46	0.21	Reef, Distance to 200 m

**Video 1.** A selection of photographs and videos illustrating the stereo-BRUV deployment method and representative fish assemblages of the nearshore Pilbara region of north-western Australia.

**Figure 1.** Location of 212 stereo-BRUV deployments conducted in the Pilbara region of north-western Australia.

**Figure 2.** Spatial distribution of the relative abundance of five fishery targeted species and of species richness observed on stereo-BRUV deployments in the inshore Pilbara region of Western Australia. MaxN bubble sizes reflect actual numbers and therefore sizes on the plot may be larger or smaller than those in the legend, depending on numbers observed. \* Most important variables for explaining the relative abundance of each species/group (see Table 1).

**Figure 3.** Spatial distribution of the relative abundance of the five most common fish species observed on stereo-BRUV deployments in the inshore Pilbara region of Western Australia. MaxN bubble sizes reflect actual numbers and therefore sizes on the plot may be larger or smaller than those in the legend, depending on numbers observed. \* Most important variables for explaining the relative abundance of each species/group (see Table 1).

**Figure 4.** Spatial distribution of the relative abundance of the five most common fish families observed on stereo-BRUV deployments in the inshore Pilbara region of Western Australia. MaxN bubble sizes reflect actual numbers and therefore sizes on the



plot may be larger or smaller than those in the legend, depending on numbers observed.

\* Most important variables for explaining the relative abundance of each species/group  
(see Table 1).

**Figure 5.** Percent cover of hard corals, soft corals, macroalgae and reef and estimates of relief and SD relief from stereo-BRUV deployments in the inshore Pilbara region of Western Australia. MaxN bubble sizes reflect actual values and therefore sizes on the plot may be larger or smaller than those in the legend, depending on values observed. \* The key species groups for which these variables were important (see Table 1).

**Figure 6.** Relative importance of each explanatory variable in predicting species richness, total abundance and the relative abundance of target and common species and families. Each value was calculated as the average Akaike weight (wAIC) of all subsets of models containing that variable, which was then scaled between 0-1 and multiplied by the R<sup>2</sup> of the best fitted model.

**Figure 7.** The total residual abundance, species richness and the residual abundance of four fishery targeted species in the Pilbara relative to their most important explanatory variables (Table 1). Models were fitted using GAMMs. The solid black line represents the estimated smoothing curve and dashed lines represent  $\pm 2 \times \text{SE}$  of the estimate.

**Figure 8.** The residual abundance of the five most common fish species in the Pilbara relative to their most important explanatory variables (Table 1). Models were fitted

826 using GAMMs. The solid black line represents the estimated smoothing curve and  
827 dashed lines represent  $\pm 2 \times \text{SE}$  of the estimate.

828

829 **Figure 9.** The residual abundance of the four most common fish families (excluding  
830 Carangidae) in the Pilbara relative to their most important explanatory variables (Table  
831 1). Models were fitted using GAMMs. The solid black line represents the estimated  
832 smoothing curve and dashed lines represent  $\pm 2 \times \text{SE}$  of the estimate. Carangidae is  
833 excluded here due to the null model having the best fit.