Key Ecological Processes in Kimberley Benthic Communities: Fish Recruitment

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WAMSI Kimberley Marine Research Program

Final Report

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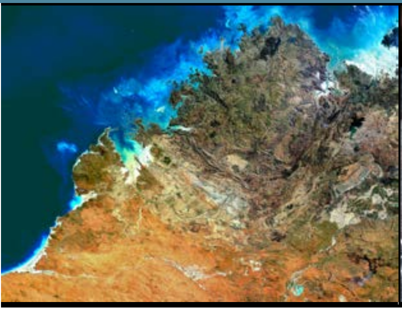

WAMSI Kimberley Marine Research Program

Initiated with the support of the State Government as part of the Kimberley Science and Conservation Strategy, the Kimberley Marine Research Program is co-invested by the WAMSI partners to provide regional understanding and baseline knowledge about the Kimberley marine environment. The program has been created in response to the extraordinary, unspoilt wilderness value of the Kimberley and increasing pressure for development in this region. The purpose is to provide science based information to support decision making in relation to the Kimberley marine park network, other conservation activities and future development proposals.

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Front cover images (L-R)

Image 1: Satellite image of the Kimberley coastline (Image: Landgate)

Image 2: Bite marks on seagrass from the herbivorous golden-lined rabbitfish *Siganus lineatus* (Image: Matt Vanderklift)

Image 3: Humpback whale breaching (Image: Pam Osborn)

Image 4: Juvenile mangrove jack *Lutjanus argentimaculatus* (maarrarn) (Image: CSIRO)

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http://www.marlin.csiro.au/geonetwork/srv/eng/search#!8d910bf0-2f4e-4fc2-8a6e-f0447ed2d996
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Author Contributions

MD, TH, MG, CP, MT & SW designed the field techniques and sampling programs; MD, KC, TH, MG, CP, MT & SW conducted the fieldwork; KC, SW, CP & MD conducted data analyses; KC and two independent contractors conducted video analyses (Todd Bond, Matt Birt, The University of Western Australia). MD & KC wrote the report.

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Contents

Executive summary

Fish recruitment, the process of juvenile fish moving into adult populations, is a fundamental determinant of population size. It is often measured as the local abundance of juvenile fish, although there are often some locations, habitats or times of year where recruitment of fish is higher than others. Consequently, knowing when and where recruitment is highest identifies ecologically important times and locations which can inform conservation and fisheries management. As measures of recruitment are also dependent on the technique employed it is imperative that location and taxa appropriate methods are developed to acquire relevant recruitment information.

Our research remit was to develop techniques suitable to quantifying juvenile fish recruitment in the challenging macro tidal conditions of the Kimberley (how); provide baseline levels of abundance and diversity across a range of representative Kimberley marine habitats (how many), identify the seasonal timing of fish recruitment (when); identify important juvenile fish nursery grounds or habitats (where) and provide advice on relevant sites as a basis for any future monitoring. In collaboration with the Bardi Jawi Rangers and the Kimberley Marine Research Station, this research was focused in the Cygnet Bay and Sunday Island group at the mouth of King Sound in the Western Kimberley. In total, a series of eight fish recruitment field trips were completed from March 2015 - March 2016.

Our initial pilot study (March 2015) compared seven separate fish recruitment sampling techniques across six locations which together encompassed four different habitats; inter-tidal pools, seagrass, mangrove and coral reefs. Following analyses that considered sampling effort, ability to accurately quantify juvenile fish diversity and abundance across a range of habitats, precision and safety, unbaited stereo remote underwater video (stereo-RUVs) was shown to be the most appropriate technique. This method is well suited to monitoring in the Kimberley, however, it is not commonly employed to measure fish recruitment, making it difficult to make comparison with other studies. During this pilot study, it also became clear that tidal current strength and habitat type were critically important variables structuring fish recruitment patterns. To address this, we restricted core sampling to neap tides or 1.5 hours either side of spring high and low tides and added in algal meadows as a fifth habitat.

In total, we recorded 125 species of adult and juvenile fish during surveys. Eleven (9%) of these were observed only as juveniles, 43 (33%) as both juveniles and adults, and 74 (60%) only as adults. Among species, 88% of all recorded juveniles were represented by the top 12 species. Interestingly, many of these are considered as highly valued species to the Bardi Jawi community (e.g. Mangrove jack, Golden-lined rabbitfish, Spanish flag) because of their dietary and/or cultural significance.

Among habitats, mangroves, seagrass and algal habitats were all represented by juvenile fishes from 18-20 species, intertidal pools by 13 and coral reefs by 35 species with only 6% of the species pool observed in all five habitats. A closer look at the distribution of species among habitats revealed very distinct partitioning of nursery grounds. Our analyses showed that mangroves and seagrass areas were critical nursery habitats for many important species and that many of these species exclusively recruited to these habitats. In comparison, the other three habitats shared a common species pool indicating that any future sampling should concentrate on mangrove, seagrass and, given their increased diversity, coral reef habitats to provide comprehensive coverage of fish recruitment. Our findings therefore support the need for representative protection of all these habitats to ensure conservation of the full cohort of fish biodiversity.

Seasonally, fish recruitment was strongest in the wet season (March / April) for most species although there were exceptions. Interestingly, some of the species considered most important to the local indigenous community are species that we identified as having strong year round recruitment providing scientific support for documented traditional Bardi Jawi fishing knowledge and management practices.

Our sampling program provides a blueprint for future monitoring of fish recruitment in the challenging Kimberley marine environment. Here we have established best-practice sampling techniques, provide locations of appropriate monitoring sites for quantifying juvenile fish recruitment across a range of representative habitats to form the basis for future long-term monitoring in the southern Kimberley region. Regular monitoring enables

assessments of how recruitment influences adult populations relative to other anthropogenic pressures (e.g. fishing, climate change). As such recruitment surveys should be conducted in conjunction with monitoring of ecologically, recreationally, commercial and culturally significant adult fish, which are typically the focus and priority of monitoring programs.

1 Introduction

Fish population replenishment typically occurs via recruitment of larvae from offshore pelagic into shallow-water environments where they settle and grow into juveniles (Cowen et al. 2007). The supply of new recruits is inconsistent and varies enormously between years, seasons, locations and habitats for various reasons (Doherty & Williams 1988, Doherty 1991). Among other factors, the number of mature adults and their reproductive output, oceanographic currents, sea temperature, pelagic food supply and behavioural aspects of larval fishes all contribute to variation in the rates of supply of new recruits (Russell et al. 1977, Robertson et al. 1999). Additionally, once newly-recruited fishes settle into shallow water environments, the rates of juvenile survivorship also vary greatly due to ecological factors linked to resource availability (*e.g.* food and habitat) and predation rates (Jones 1991, Trip et al. 2014). The net outcome of all these processes determines the future of adult fish populations (Hixon et al. 2012, Wilson et al. 2016). Therefore, understanding the spatial and temporal patterns of fish recruitment processes is crucial for assessing the future of fish populations and developing local management and conservation strategies.

The Kimberley region is rich in biodiversity (Wilson 2013) and remains one of the least explored and pristine marine ecosystems on the planet (Halpern et al. 2008), although the region is under increasing stress from climate change (Halpern et al. 2015). Like most ecological processes, fish recruitment in the Kimberley is poorly described or understood (DEWHA 2007) although patterns of shelf and offshore fish larval distribution have been investigated (Holliday D, 2011). Compounding this lack of information, the environment of the Kimberley region is complex and unique. Daily tidal ranges of up to 12 m, a labyrinth of islands that funnel and accelerate multi-directional water flow, significant seasonal freshwater input and complex bathymetry (Wilson 2013, Lowe et al. 2016) bring together complex conditions for larval/juvenile fishes whether they be transiting from a pelagic to a benthic environment, or have already metamorphosed and settled to shallow coastal waters. These complex conditions are likely to both help and hinder fish recruitment processes to nearshore areas. For example, strong tidal flows affect larval transport into shallow water environments depending on the timing and alignment of recruits with moon and daily tidal cycles (Stephens et al. 2006). Strong tidal currents and associated reef circulation may also bring more planktonic food to growing recruits but at the same time make waters turbid, possibly reducing foraging success and overall survivorship (De Robertis et al. 2003).

Research over the past two decades has shown that self-recruitment back to natal habitats is an important feature in tropical marine fishes making up anywhere between 15-89% of recruitment numbers (Jones et al. 1999, 2005, Swearer et al. 1999). Since this finding, attention has focused on how larval fishes are able to navigate back to their parent's birthplace. This body of work has shown astonishing evidence of very sophisticated behaviour (*e.g.* position in water column to facilitate directional travel, strong and sustained swimming ability) and sensory faculties (sight, smell, sound) that help explain this phenomenon (Fisher et al. 2000, Leis et al. 2003, Paris & Cowen 2004, Simpson et al. 2005, Dixson et al. 2008). But how well do these faculties and features operate under the extreme hydrological conditions of the Kimberley? Recent genetic evidence in two fish species (the benthic egg layer damselfish *Pomacentrus milleri* and the open-water spawning snapper *Lutjanus carponotatus* using single nucleotide polymorphism markers) suggests demographically independent populations exist between the Kimberley and neighbouring Pilbara Regions (Berry et al. 2016). This and other studies in the region indicate that, unlike the Pilbara region of Western Australia, genetic exchange within the Kimberley region itself as well as among offshore shoals can be surprisingly limited (in the order of hundreds of kilometres) in a number of taxonomic groups including fish (Underwood et al. 2012). This suggests that the extreme hydrological conditions in the Kimberley can promote genetic retention rather than widespread dispersal of fish larvae, and that local adult fish stocks may have a comparatively large influence on the patterns of recruitment strength within localised areas of the Kimberley. High rates of self-recruitment may therefore be a strong feature in this region, making the assessment of local recruitment processes and their variation particularly relevant for understanding and managing local fish populations.

Indigenous Australians have been managing their own aquatic resources for millennia (Yunupingu & Muller 2009, Noble et al. 2016). The Kimberley coastline not only plays a significant role in the daily lives of indigenous people by providing natural resources, but is also deeply embedded in their social, cultural and spiritual values. There are many examples of traditional codes of best practice governing conservation measures such as seasonal restrictions on marine resource extraction, off-limit areas and limits to catch sizes (Ross & Pickering 2002). These conservation measures are based on knowledge, which is collectively termed “indigenous knowledge”, and based on “traditional ecological knowledge” that has been honed over historical time periods through trial and error (Gadgil et al. 1993). However, modern day coastal Australia including the Kimberley is facing growing pressures from many new sources. Increased commercial, recreational and indigenous fishing, coastal development, tourism and industry are all potential threats to finfish. In addition, forces such as climate change which affects sea temperatures, food and habitat resource supply and quality, freshwater regimes and incidences of damaging disturbances such as storms and cyclones are also increasing and relevant to modern management (Wu et al. 2012, Cai et al. 2015). Faced by unprecedented pressures on marine resources, there is a shared realisation by indigenous and non-indigenous managers alike that the integration of traditional knowledge systems and western science provides a potent way in which to better understand our coastline ecosystems in order to meet and respond to these new challenges. Providing baselines for fish recruitment across space and time in the Kimberley is therefore timely and an important step towards providing a rigorous way to measure any future effects of chronic or acute anthropogenic and non-anthropogenic pressures on local fish populations.

The benefits of understanding fish recruitment processes include providing an indication of future demographic trends (*e.g.* Wilson et al., 2016), identifying nurseries of importance (*e.g.* Dorenbosch et al., 2006; Evans et al., 2014), assessing the general and continued health and well-being of fish fauna within an ecosystem, understanding the potential for recovery following an acute disturbance, and providing a way to identify and understand the mechanisms responsible for recruitment processes into particular areas (Sale 1980, Wilson et al. 2006, Halford & Caley 2009). Understanding fish recruitment is therefore very relevant to the spatial management of fish stocks for indigenous and government agencies tasked with conservation planning and policy.

Here, we document the spatial and seasonal patterns of fish recruitment in the Cygnet Bay Sunday Island area of the Western Kimberley during a 12 month period, with an aim to;

1) Develop cost-effective techniques suitable to the Kimberley marine region that, wherever possible, allow direct comparisons with other data-sets in Western Australia
2) Provide baseline quantitative information on levels of fish recruitment across a gradient of commonly available Kimberley habitats
3) Identify seasonal trends in fish recruitment for selected important species
4) Provide an overview of the relative importance of representative habitats to fish recruitment processes
5) Identify possible biodiversity hotspots and population strongholds for juvenile fishes
6) Establish monitoring sites to form the basis for a future long-term monitoring program

Before fish recruitment could be properly surveyed, an in-depth investigation to develop an appropriate sampling technique for the Kimberley was completed, given the extreme hydrodynamic conditions of the region, which make traditional diver-based methods of quantifying fish recruitment unfeasible (see Depczynski et al. 2015). New remote methods to suit Kimberley conditions had to be developed, tested, refined and compared to each other in order to provide the best alternative to traditional diver-based methods. In addition to the challenging hydrology, the Kimberley benthos is typically composed of a mosaic of overlapping habitats rather than categorically homogenous environments (Wilson 2013). Given that many fish species either have a preference for or even exclusively recruit and grow up in specific nursery habitats (Dorenbosch et al. 2006, Wilson et al. 2010), it was necessary that the method chosen could adequately deal not only with extreme hydrological conditions but also sample all types and combinations of habitats. Ultimately, the method chosen was a replicated set of remote underwater stereo-video stations (RUVs) that could be safely deployed in all coastal habitats identified and were able to adequately capture differences in the community structure of fish recruits. The method used twin cameras allowing accurate size measurements (Cappo et al. 2003, 2006), which were required to delineate recruits from adults based on size cut-off points for adult *vs*. juvenile life stages. Stereo-RUVs proved to be the best technique for assessing spatiotemporal variation in fish recruitment patterns in the Kimberley. A full and detailed analysis of technique comparisons can be found in Depczynski et al. (2015) and is summarised in the next section.

2 Materials and Methods

As described above, a pilot study aimed at developing, testing and refining cost-effective techniques suitable to quantifying juvenile fishes in the testing Kimberley conditions was undertaken during the wet season in April 2015 (see Depczynski et al. 2015). In summary, seven techniques: remote underwater stereo-video systems (RUVs), rotenone, box trawls, drop cameras, and underwater visual census (transect, stationary and block), were thoroughly trialed at six locations which together encompassed four contrasting habitats; intertidal rockpools, seagrass, mangrove and coral reefs. A further two techniques were explored, but deemed unsuitable before the field trial stage. Although no single technique was able to comprehensively capture the full diversity of the Kimberley juvenile fish assemblage within any habitat, stereo-RUVs was the most consistent technique across habitats (Depczynski et al. 2015). RUVs were also the only technique that could be used successfully in all four habitats importantly allowing among-habitat comparisons to be made. In fact, RUVs were the only method to successfully record juvenile fishes in mangroves. Additionally, they provide a permanent record, are safe to use (do not require divers), repeatable, easily deployed and reasonably time efficient in providing precise estimates of abundance and acceptable levels of diversity when compared to all other techniques trialed. Finally, stereo-video techniques have previously proved successful for sampling small fishes (<300 mm total length; Davis et al. 1997, Norcross & Mueter 1999, Cappo et al. 2006, Santana-Garcon et al. 2014). Precision estimates indicated that five replicate RUV units were sufficient to ensure robust quantification of juvenile fishes for each location *x* habitat combination providing an efficient and consistent method to address the aims outlined above.

2.1 Study location

This study was conducted in shallow nearshore habitats in the Cygnet Bay and Sunday Island areas in the western Kimberley, northwest Australia (approx. 16.5°S, 123°E, see Appendix 1 for specific site details) (Figure 1). The Sunday Island group forms a string of islands at the tip of the Dampier Peninsula that extends to the east across the opening of King Sound. The area is rich in biodiversity, with high levels of endemism and a mosaic of habitat types including intertidal rockpools, mangroves, seagrass and algal beds, and well developed coral reef systems (Fox & Beckley 2005, Thorburn et al. 2007, Jones et al. 2015).

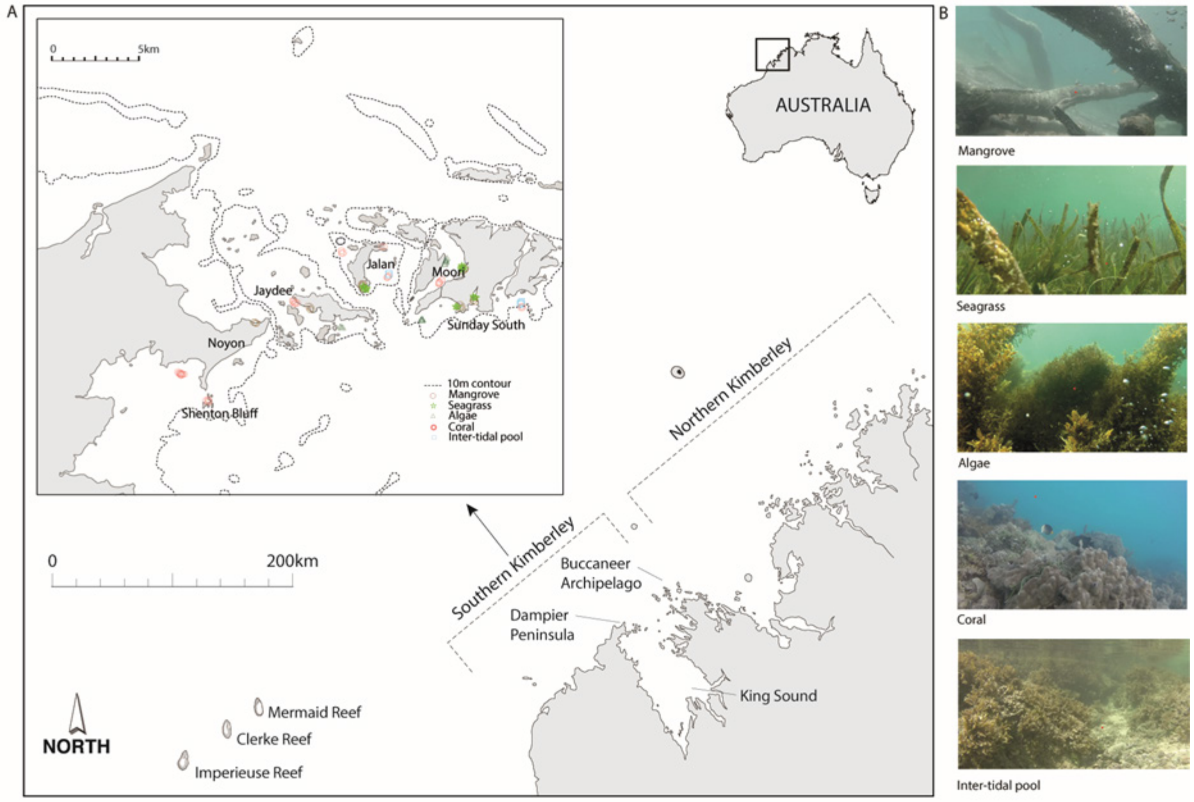

Figure 1. Map of the six study locations in the Cygnet Bay and Sunday Island areas of the western Kimberley region in northwest Australia (Jaydee= Jackson Island, Jalan= Tallon Island) (a). Stereo-RUV deployments were conducted during wet (March-April 2016) and dry (October 2015) seasons in five different nearshore habitats (mangroves, seagrass beds, macroalgal beds, submerged coral reefs, and inter-tidal rockpools, b), and bi-monthly at coral reefs. Each location by habitat combination was treated as a site, and stereo-RUVs replicated randomly at each site through time. For sampling details see Tables 1 and 2.

The diverse coastal and marine communities of the western Kimberley region are strongly influenced by the unique oceanography of the area. Tidal ranges of up to 12 m occur on spring tides twice a day, creating tidal currents of up to 10 knots (Purcell 2002, Lowe et al. 2015), with the biggest tides occurring towards the end of the rainy season from March to April (Ruprecht & Rogers 1998). During these extreme tidal fluxes coastal ecosystems may be completely exposed to air for up to four hours, resulting in daily sea temperature fluctuations of up to 7^{o}C in very shallow or intertidal areas, to which local organisms such as corals have become adapted (Purcell 2002, Richards et al. 2015, Schoepf et al. 2015). On coral reef habitats in particular, tidal fluxes create large intertidal reef terraces that alternate between periods of complete submersion and exposure, and create a series of intertidal rockpools of differing size (Purcell 2002, Schoepf et al. 2015).

2.2 Sampling design and methods

To evaluate spatial trends, seasonal trends, and habitat preferences in patterns of fish recruitment, two separate studies were conducted using stereo-RUV deployments replicated at six locations. In the first study, seasonal trends across all five habitats were assessed during wet (March-April) and dry (October) seasons (Figure 1, Table 1). The second study was aimed at further exploring temporal patterns in fish recruitment on a bi-monthly basis over a 12-month period (Oct 2015 – Aug 2016) in subtidal coral reef habitats only (Table 2), which were taken as a higher-resolution proxy for temporal patterns in all other habitats. All drops were made in water depths between 0.4 and 6.9 m. To minimise the effects of extreme tidal currents, drops were either timed to coincide with neap tides or restricted to one hour either side of peak high and low spring tides to facilitate identifications by minimizing turbidity while sampling. All habitats within each location were separated by at least one kilometre with the exception of mangrove and seagrass beds, which were usually found adjacent to each other.

Stereo-RUV deployments were all unbaited because of the potential biases of bait attracting predators of juvenile fishes and therefore limiting their appearance in the field of view (Harvey et al. 2007). Stereo-RUV units consisted of two GoPro Hero 3+ video cameras in waterproof housings mounted on a custom made base bar made of light aluminium frame (SeaGIS Pty. Ltd; www.seagis.com.au, Figure 2). Each system was optimised for sampling of smaller bodied fishes with video cameras mounted 0.4 m apart on the base bar, and converged inwardly at a 6° angle, resulting in an optimised field of view with stereo-coverage from 0.5 m in front of the cameras outwards to 3 m. Stereo-RUV units were calibrated in a pool prior to deployment in the field using a standard calibration cube (www.seagis.com.au).

Five stereo-RUVs separated by a distance of 50 m were deployed consecutively during daylight hours from a small vessel (10 m) at each location x habitat combination (*i.e.* site) and left to record for 20 minutes. We chose 20-min deployments as optimal based on a combination of video analysis/field efficiency and pilot study data calculations based on species and abundance accumulation curves, which identified maximum species diversity and relative abundance of juvenile fishes was adequately captured within this period (C Piggott unpublished data). We also judged 50 m spacings of replicate units to be sufficiently well spaced on the basis of the restricted home ranges of most juvenile fishes. The same sampling design was followed on subsequent surveys (seasonal and bi-monthly) at each of the sites surveyed, with specific RUV deployment locations selected at random within each site.

Table 1. Summary of stereo-RUV deployments during the wet (March-April 2016) and dry (October 2015) seasons at five habitats (mangrove, seagrass, algae, coral and inter-tidal rockpools), across six locations in the Sunday Islands, western Kimberley. A total of 151 stereo-RUVs were deployed in the region, across 17 sites (location x habitat combination).

	Mangrove		**Seagrass**		**Algae**		**Coral**		**Inter-tidal pools**	
Location	***wet***	***dry***	***wet***	***dry***	***wet***	***dry***	***wet***	***dry***	***wet***	***dry***
ShentonBluff	0	0	0	0	0	0	5	5	0	0
Noyon	5	0	0	0	0	0	5	4	0	0
Jaydee	5	4	0	0	5	3	5	5	0	0
Jalan	4	5	5	5	0	0	0	0	5	0
Moori	4	3	5	4	5	5	4	5	0	0
SundayIsland	5	5	4	4	4	5	0	0	8	6
Total	*23*	*17*	*14*	*13*	*14*	*13*	*19*	*19*	*13*	*6*

Table 2. Summary of bi-monthly stereo-RUV deployments at subtidal coral reef habitat across five locations in the Sunday Islands, western Kimberley. A total of 107 stereo-RUVs were deployed at coral reef habitat during the 12 month period. *Note that location and site are equivalent for this dataset, given that only coral reef habitat was surveyed.

Location	**Oct15**	**Dec15**	**Feb16**	**Mar/Apr16**	**May16**	**Jul/Aug16**
Noyon	4	5	0	5	4	5
Jaydee	5	5	4	5	4	0
Jalan	0	5	3	4	3	5
Moori	5	4	4	4	5	4
SundayIsland	0	0	5	5	0	5
Total	*14*	*19*	*16*	*23*	*16*	*19*

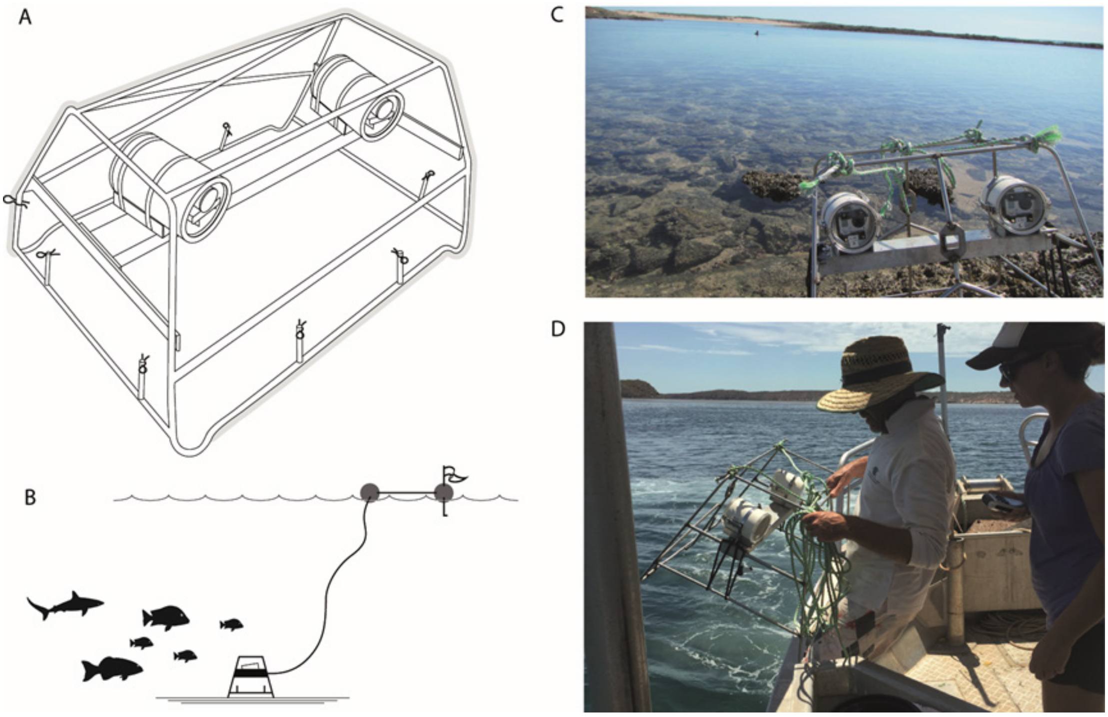

Figure 2. Diagram showing the design (a), functioning (b) and deployment of stereo-RUV units at an inter-tidal rockpool (c) and from a small vessel (d) in the western Kimberley.

2.3 Image analyses

2.3.1 Fish assemblages

Video footage was analysed using the software EventMeasure™ (SeaGIS Pty. Ltd), following calibrations using the software CAL (SeaGIS Pty. Ltd) (Harvey & Shortis 1998). All fish recorded within 3 m of the cameras were identified to the lowest taxonomic level possible, measured (to the nearest 0.1 mm) and categorised as juvenile or adult (see criteria below). All planktonic schooling fishes from the families Caesionidae (fusiliers) and Clupeidae (sprats/anchovies) were excluded from the analyses because of their lack of site fidelity to distinct habitats and potential to bias fish recruitment patterns. To avoid repeat counts of individual fish re-entering the field of view, a conservative measurement of relative abundance (MaxN) was recorded. MaxN is defined as the maximum number of individuals of the same species appearing in a single paused frame (Priede et al. 1994). MaxN was recorded separately for adult and juvenile fishes, resulting in two separate MaxN 'by life-cycle stage' measurements per species.

Individuals were classified as juvenile based on colouration and body size (L_{33}, <33% of maximum adult total length) (Nagelkerken & van der Velde 2002, Dorenbosch et al. 2005). Information on maximum adult total length (L_{max}) for each species was obtained preferentially from published literature (Allen & Swainston 1988, Allen et al. 2003) or FishBase (www.fishbase.org) in circumstances where no published literature existed. For individuals that could not be reliably identified to species, the average L_{max} of the three most likely species was used to calculate L_{33}. Juvenile fish lengths (Total length [L_T]) were taken at the corresponding MaxN 'by life-cycle stage' frame, to avoid making repeated measurements of the same individuals. In order to get a better side view of each individual for measurement purposes, if required, video frames were advanced from the time of MaxN, making sure individual fish were followed through the sequence. Where a measurement of an individual fish was not possible (*e.g.* bent position, present in only one camera, bad visibility etc.), it was conservatively classified as an adult and discounted from the juvenile data set. All video analyses were performed by three experienced observers (KC, TB, MB) under the same set of strict guidelines. Cross-checking of a subset of videos between observers was then conducted in order to guarantee consistency for both MaxN and species identification.

2.3.2 Habitat variables

Habitat type for each stereo-RUV deployment was initially classified into five categories: mangrove, seagrass, algae, coral and inter-tidal rockpools, based on the general habitat targeted during each RUV deployment. Initial exploration of RUV videos indicated that these habitat categories were often a mosaic of overlapping habitats. For this reason we estimated more detailed habitat composition measures for each stereo-RUV, so that we were able to define patterns of fish recruitment (abundance and species composition) based on continuous, rather than categorical habitat data. This provided a more robust and realistic picture of the benthic habitat in the Kimberley. Continuous habitat data (% cover) were estimated following the rapid annotation methods described in McLean et al. (2016) and using the software TransectMeasure™ (SeaGIS Pty. Ltd). Benthic composition for each stereo-RUV deployment was quantified along a 5 x 4 grid overlaid onto a high definition habitat image obtained from each RUV deployment. The dominant habitat type at each of these grid rectangles was classified according to seven broad benthic categories: hard corals, consolidated substrates, macroalgae, mangroves, seagrasses, sponges and unconsolidated sediments, following the CATAMI classification scheme (Althaus et al. 2013). An 'open water' category was included for rectangles where no biota was present.

2.4 Data analyses

Two juvenile fish datasets were generated for statistical interrogation following video analyses; a wet *vs.* dry season analysis targeting fish recruitment patterns across all five habitat types; and a bi-monthly analysis for the coral reef habitat only (see Tables 1 & 2). We used univariate generalised additive mixed models (GAMMs) to investigate patterns of abundance and multivariate distance-based linear models (DistLMs) to examine changes in community composition for each data set. In all models, habitat was treated as a continuous variable (% cover or proportion), season and sampling period (for bi-monthly surveys) as factors, and site (*i.e.* each location x habitat combination) as a random effect. Habitat variables were transformed (log10(x + 1) or square root) where necessary to downplay outlying values and better represent relationships with juvenile fish abundance and species composition.

For both univariate and multivariate models, variable importance metrics were calculated for each predictor variable based on weighted Akaike's information criterion values corrected for finite sample sizes (wAICc) (Burnham & Anderson 2002). Variable importance metrics assisted model interpretation and allowed identification of the most important predictors of the relative abundance of juvenile fishes and their species composition. Each variable importance value was calculated as the average Akaike weight of all subsets of models containing that variable, scaled between 0 and 1 and multiplied by the R^2 value of the best fitted model.

2.4.1 Patterns of abundance

GAMMs were fitted to univariate data on total juvenile fish abundance (MaxN per replicate) with package 'mgcv' in R version 3.3.1 (R Development Core Team 2014). GAMMs were chosen due to their capacity to deal with non-linear relationships between dependent and continuous predictor variables (Austin 2007), and their inclusiveness of random effects that account for correlation between observations on the same sampling unit (*e.g.* RUV deployments within site). GAMMs with all possible variable subsets were fitted to untransformed juvenile fish relative abundance data, and the appropriate distribution used for model analyses (*i.e.* Gaussian distribution with log-link function for seasonal data, and Poisson for bi-monthly data). Models containing variables with a correlation >0.40 were excluded from the full subset of models to eliminate strong collinearity. Model selection was based on AICc, which was used to compare models and select the most parsimonious one (*i.e.* fewer number of predictors and within two AICc units of the model with the lowest AICc value).

2.4.2 *Patterns of species composition, temporal recruitment of selected species and species diversity*

For multivariate data on species composition, we used DistLMs (Legendre & Anderson 1999) to better understand spatiotemporal patterns in the juvenile fish assemblage. A Bray-Curtis dissimilarity matrix was calculated for square root transformed data on fish abundance at the species level (MaxN per species per replicate), and DistLMs fitted using a full subsets approach excluding models with correlated variables (>0.40). Model selection procedures to choose the most parsimonious model were based on a multivariate analogue of the AICc in a manner equivalent to that described for GAMMs above (see Anderson et al. 2008). Analyses used the PERMANOVA+ add-on package for PRIMER v.6 (Anderson et al. 2008). Distance-based redundancy analysis (dbRDA; Legendre & Anderson 1999), a form of ordination, was then used to visualise the chosen model with vectors overlaid for individual fish species, habitat variables (% cover) and factors (season or sampling period); only vectors with Pearson correlations >0.25 with the dbRDA axes were included.

For a more in-depth exploration of temporal recruitment patterns in the most abundant juvenile fish species in the Kimberley region, we constructed basic summary plots of average juvenile fish abundance (MaxN ± SE) pooled across habitats during each season, and at coral-reef habitat during each sampling period. In addition, we used fish length data (L_T) on the most abundant juvenile species, to produce length-frequency distributions pooled at either the season or sampling period level, taking all length measurements irrespective of habitat surveyed. Bin-widths for length-frequency distributions were selected according to the maximum juvenile length for each species (L_{33}, <33% of maximum adult total length). Finally, we constructed species accumulation curves to examine species diversity at the five general habitat types surveyed (mangroves, seagrasses, algae, corals and inter-tidal rockpools), and during wet *vs.* dry seasons. These curves allowed us to compare the number of species present at each habitat type, while taking into account dissimilarities in sampling effort between habitats, and were fitted using the 'vegan' package in R version 3.3.1 (R Development Core Team 2014).

3 Results

3.1 General abundance and species diversity patterns

We identified 125 fish species from 22 families. Eleven (9%) of these species were observed only as juveniles, 43 (33%) as both juveniles and adults, and 73 (60%) only as adults (Appendix 2). Of the species for which juveniles were observed, detected abundance was mostly low, with 88% of the abundance represented by only 12 species (*Choerodon cyanodus*, *Scarus JHC sp3*, *S. ghobban*, *Lutjanus carponotatus*, *Gerres oyena*, *Scaevius milii*, *Dischistodus darwiniensis*, *Siganus lineatus*, *S. doliatus*, *Lethrinus laticaudis*. *Acanthurus grammoptilus* and *Plectropomus maculatus*), and 39% of total abundance represented solely by *Choerodon cyanodus* (igoolan). These species were the main drivers of recruitment patterns in the study area.

Overall, detected juvenile species diversity was similar among mangrove, seagrass and algae habitats (18-20 spp. in total) and lowest in the inter-tidal rockpools (13 spp.), with the coral reef habitat supporting the highest number of species (35 spp.) (Appendix 3). Only three juvenile fish species (6% of juvenile species pool) were observed in all five habitats (Appendix 3), indicating a high degree of habitat specificity among the Kimberley juvenile fish community. RUV surveys captured recruitment for at least seven of the species that are most important to the local Bardi Jawi community as a food resource (*Lutjanus carponotatus* (joorloo), *L. argentimaculatus* (maarrarn), *L. russellii* (ilnilirr), *Siganus lineatus* (barrbal), *S. doliatus*, *Choerodon cyanodus* (igoolan) and *C. schoenleinii*) (Figure 3)). Overall, recruitment was much stronger during the wet (March/April) than in the dry (October) season for all five habitats with among-habitat comparisons indicating that the lowest abundances were found in the mangroves (Figure 3).

3.2 Seasonal patterns in abundance, species diversity and assemblage structure

Our results show strong seasonal and habitat-gradient patterns in fish recruitment strength (Figure 4). Spatiotemporal variation in the total abundance of juvenile fishes was best explained by a model using a combination of mangrove presence (% cover) and season, with this model accounting for 36% of variation in the data (Figure 4a, Table 3). Total juvenile fish abundance was lowest in mangroves (Figure 4b) but showed similar values at the other four habitats surveyed: seagrass, algae, coral and inter-tidal rockpools. At all habitats, the abundance of juvenile fishes was significantly higher during the wet season (Figure 4c).

Multivariate analyses revealed that fish assemblages differed between the habitats surveyed (Figure 5a, Appendix 3). Sites clustered into three distinct groups depending on the habitat targeted: (1) mangrove, (2) seagrass, and (3) a combined group consisting of algae, coral and inter-tidal rockpools, which all had a more similar species composition (Figure 5a). The model that best accounted for the spatiotemporal variation in juvenile fish assemblages included the amount (% cover or proportion) of mangrove, seagrass and unconsolidated sediments, combined with season, which together accounted for 24% of the variation in our data set (Figure 5b, Table 3). Twelve species were significantly correlated with the dBRDA axes (>0.25) and were primarily responsible for driving separation between habitats. The snappers *Lutjanus argentimaculatus* (maarrarn) and *L. russellii* (ilnilirr) associated strongly with mangrove habitats, *Gerres oyena*, *Siganus lineatus* (barrbal) and *Scaevius milii* with seagrass, and *Pomacanthus sexstriatus* (gorno), *Acanthurus grammoptilus* (gambarl), *Choerodon schoenleinii* (baramba), *C. cyanodus* (igoolan), *Dischistodus darwiniensis* (doodany), *Lutjanus carponotatus* (joorloo) and *Lethrinus laticaudis* (madalngoorr) with the mixed cluster of coral, algae and inter-tidal pools (Figures 3 and 5a). There was also a seasonal signal in the suite of species that recruited in the wet and dry seasons respectively (Figure 5a, Appendix 4). Species such as *Scaevius milii* and *Siganus lineatus* recruited strongly during the wet season whilst *Pomacanthus sexstriatus*, *Acanthurus grammoptilus* and *Choerodon schoenleinii* recruited in higher numbers during the dry season (Figure 5a).

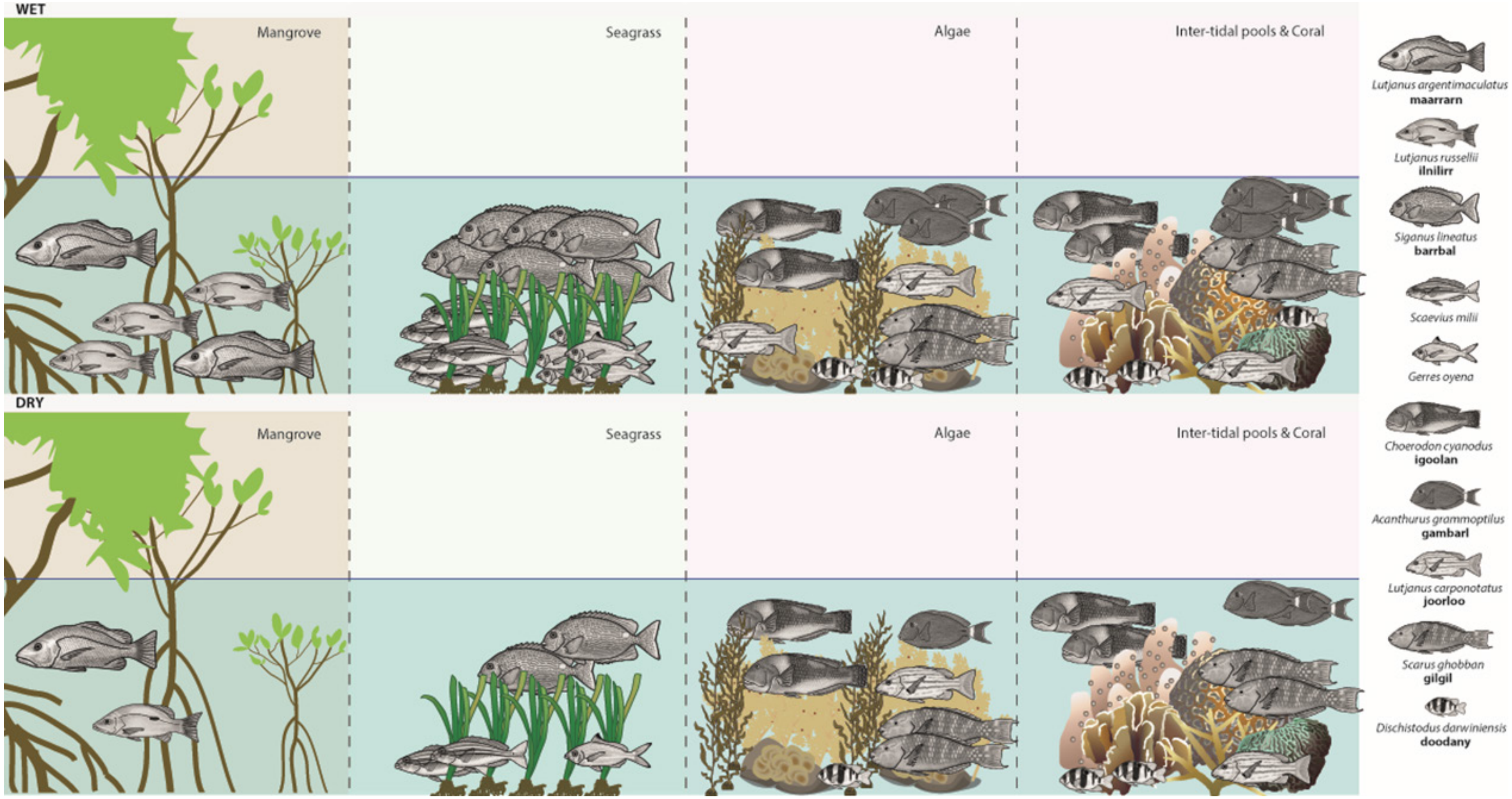

Figure 3. Graphical representation summarizing our findings from juvenile fish RUV surveys during the wet (top panel) and dry (bottom panel) seasons across five habitat types (mangrove, seagrass, algae, coral and inter-tidal rockpools; separated by dashed lines). Habitats portrayed from left to right follow a typical Kimberley habitat profile from inter-tidal mangroves to adjacent seagrass meadows and algal fields to elevated inter-tidal rockpools and submerged coral reefs. Colour shades in the background of each habitat represent groupings based on observed statistical differences in fish assemblage structure among habitats (brown - mangroves, green - seagrass, and pink - algae, coral and inter-tidal rockpools). Each fish diagram represents a different juvenile species; key to right shows scientific and Bardi Jawi names. Only the ten most abundant species distinguishing between fish assemblages at the habitat level are presented. The number of fish in each panel is equivalent to the average number of juvenile fishes per RUV replicate (*e.g.* MaxN = 5 in mangrove habitat during the wet season).

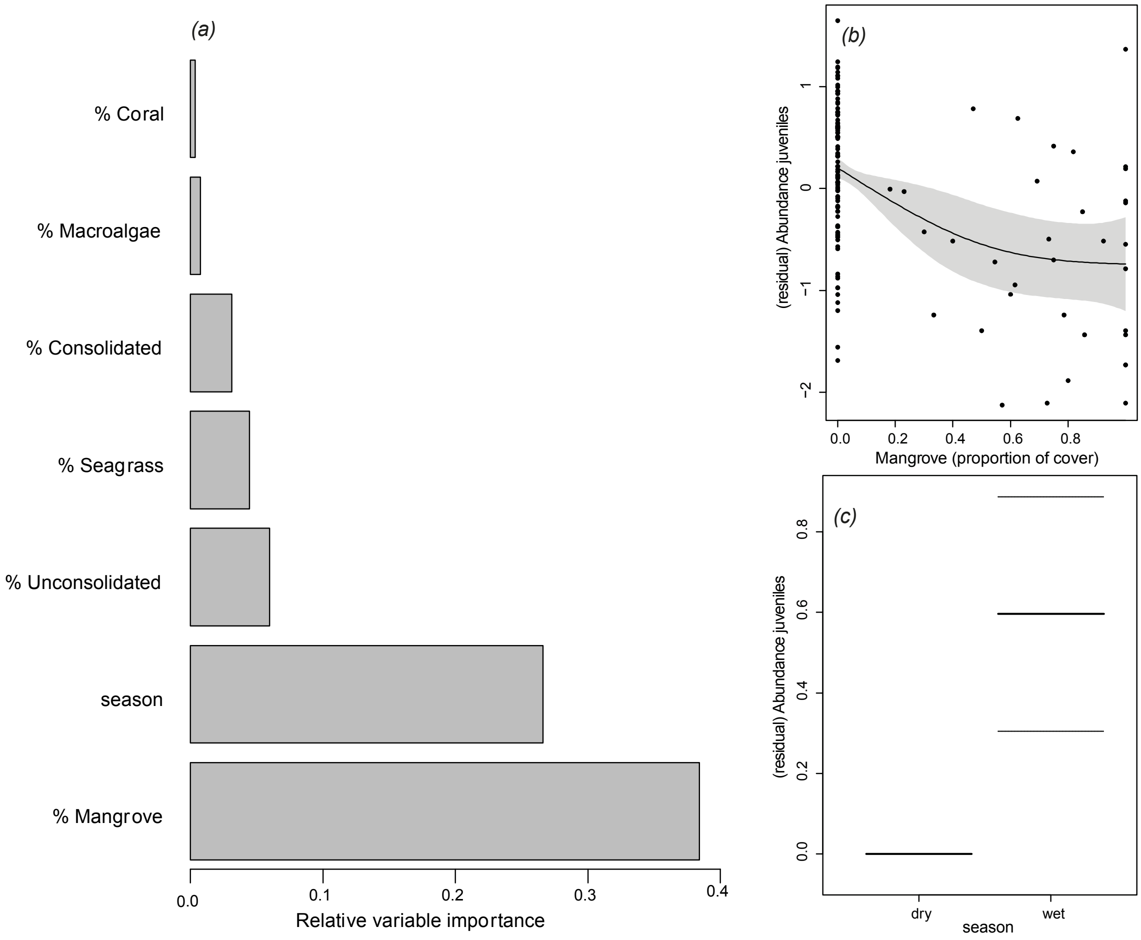

Figure 4. Graphical representation of the most parsimonious generalised additive mixed model (GAMM) for explaining variation in total abundance of juvenile fishes according to habitat (% or proportion of cover) and season surveyed; (a) shows relative variable importance for all explanatory variables used in the full subset of fitted GAMMs; (b and c) show residual abundance of total juvenile fishes in response to their most important explanatory variables: mangrove cover and season, identified via the most parsimonious GAMM (see Table 3 for model selection). Solid black lines represent model fit (estimated smoothing curve for continuous variables), and shading (b) or dotted lines (c) represent ± 2*SE of the model fit estimate.*Note there is no SE associated with the dry season in (c), because this was taken as the reference level for factor season by the model.

Table 3. Best univariate (GAMMs; *a*) and multivariate (DistLMs, *b*) models, selected from the full subset of fitted models for predicting total abundance of juvenile fishes in the southern Kimberley region. The most parsimonious model (in **bold**) had the lowest Akaike Information Criterion value corrected for finite sample sizes (AICc), and fewest variables. In (*a*) the five best GAMMs are presented and in (*b*) all DistLMs within 2 AICc units of each other.

Dependent variable	Explanatory Variables	edf	R^2	AICc
Juvenile MaxN seasonal data five habitats (# fish per RUV)				
(a) GAMMs	**Mangrove, season**	**12.65**	**0.364**	**357.469**
	Mangrove, unconsolidated, season	13.82	0.376	359.700
	Consolidated, mangrove, season	10.47	0.335	361.058
	Mangrove, seagrass, season	6.62	0.258	361.576
	Season	7.59	0.250	362.879
(b) DistLMs	Mangrove, seagrass, coral, unconsolidated, season		0.253	1057.000
	Macroalgae, mangrove, seagrass, unconsolidated, season		0.252	1057.100
	Mangrove, seagrass, unconsolidated, season		**0.239**	**1057.600**
	Macroalgae, mangrove, seagrass, coral, season		0.246	1058.300
	Consolidated, macroalgae, mangrove, seagrass, coral, season		0.257	1058.400
	Macroalgae, mangrove, seagrass, coral, unconsolidated, season		0.255	1058.700
	Consolidated, mangrove, seagrass, coral, unconsolidated, season		0.255	1058.800
	Consolidated, macroalgae, mangrove, unconsolidated, season		0.255	1058.900
	Consolidated, macroalgae, mangrove, coral, unconsolidated, season		0.254	1058.900

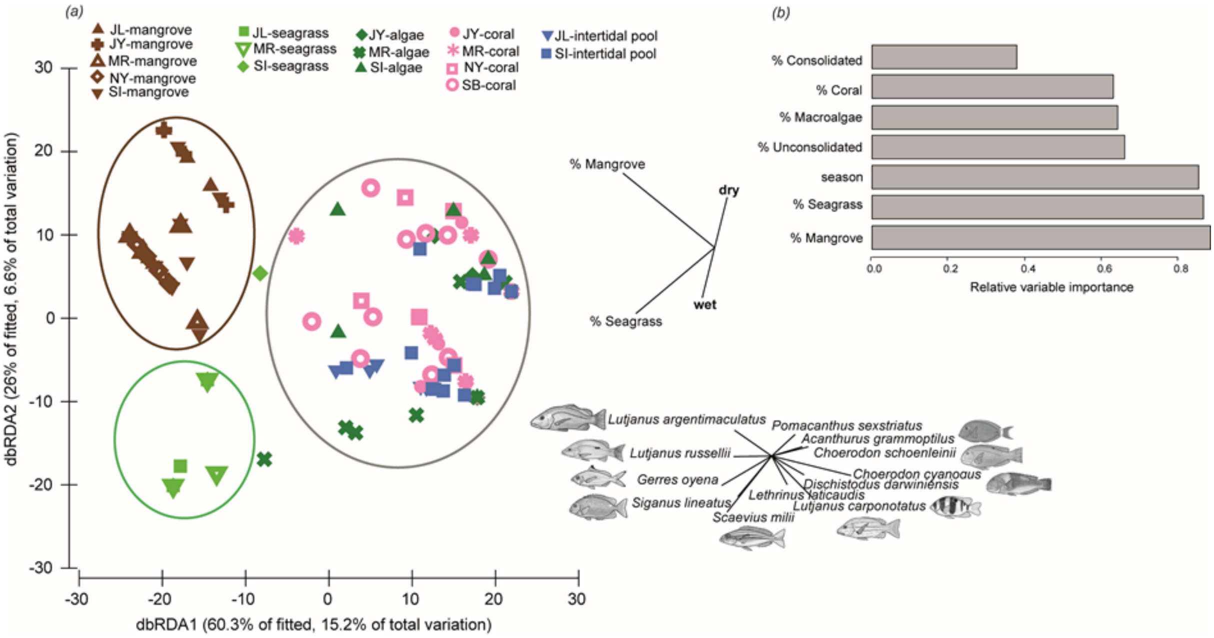

Figure 5. Distance based redundancy analyses (dBRDA) showing spatiotemporal variation in juvenile species assemblages (bottom right vectors) and significant variables explaining this variation (top right vectors) (a). Data are MaxN per RUV replicate plotted at the site level and represented by symbols and colours as shown in the legend according to habitat targeted (brown - mangrove, light green - seagrass, dark green - algae, pink - coral and blue - inter-tidal rockpools). Circles depict the three major clusters visually identified, and have no statistical significance. Relative variable importance values for all explanatory variables in the full subset of fitted distance-based linear models (DistLMs) are shown in (b); for model selection see Table 4.

3.3 Bi-monthly patterns in juvenile fish abundance and species diversity - coral reef habitat

Percentage coral cover, sampling period and % consolidated substrate cover provided the best combination of variables to explain variation in recruit abundances with 45% of total variance explained (Figure 6a, Table 4). Juvenile fish abundance was fairly constant across low to medium levels of coral cover (0 to 60%) but increased slightly from 60-80% cover before plateauing (Figure 6b). Overall, highest recruitment was seen from December to April with the highest peak in December, and weakest recruitment was observed during July to October with the lowest in July/August (Figure 6c). The influence of consolidated substrate cover (*i.e.* boulders, rock, bedrock), showed fish abundance peaked at intermediate levels of cover (Figure 6d).

Juvenile fish assemblages differed markedly between peak dry season (October) and all other bi-monthly surveys (Figure 7a, Appendix 5). This separation was mostly driven by the higher abundances of the wrasse *Choerodon schoenleinii*, coral trout *Plectropomus* spp. and angelfish *Pomacanthus sexstriatus* during peak dry season (October). Outside of October, bi-monthly surveys revealed the persistence of a more uniform juvenile fish assemblage although there were finer-scale differences observed here which also appear to relate to wet (December-March/April samples) and dry (May-July/August) survey periods. Unsurprisingly, our modelling identified period as the main influential variable (11% of variation) driving patterns in assemblage structure among bi-monthly surveys (Figure 7b, Table 4). However, coral habitats in the Kimberley are often a mix of coral and algae and both % macroalgae and coral cover were quite influential in influencing assemblage structure (Figure 7b).

In general, there was a high degree of concordance between our bi-monthly survey results and those exhibited among all habitats in our seasonal surveys suggesting that a reduced sampling design covering the end of the wet and dry seasons (*i.e.* March-April and October) provided a good representation of the spatiotemporal variation in the juvenile fish assemblages of the southern Kimberley region.

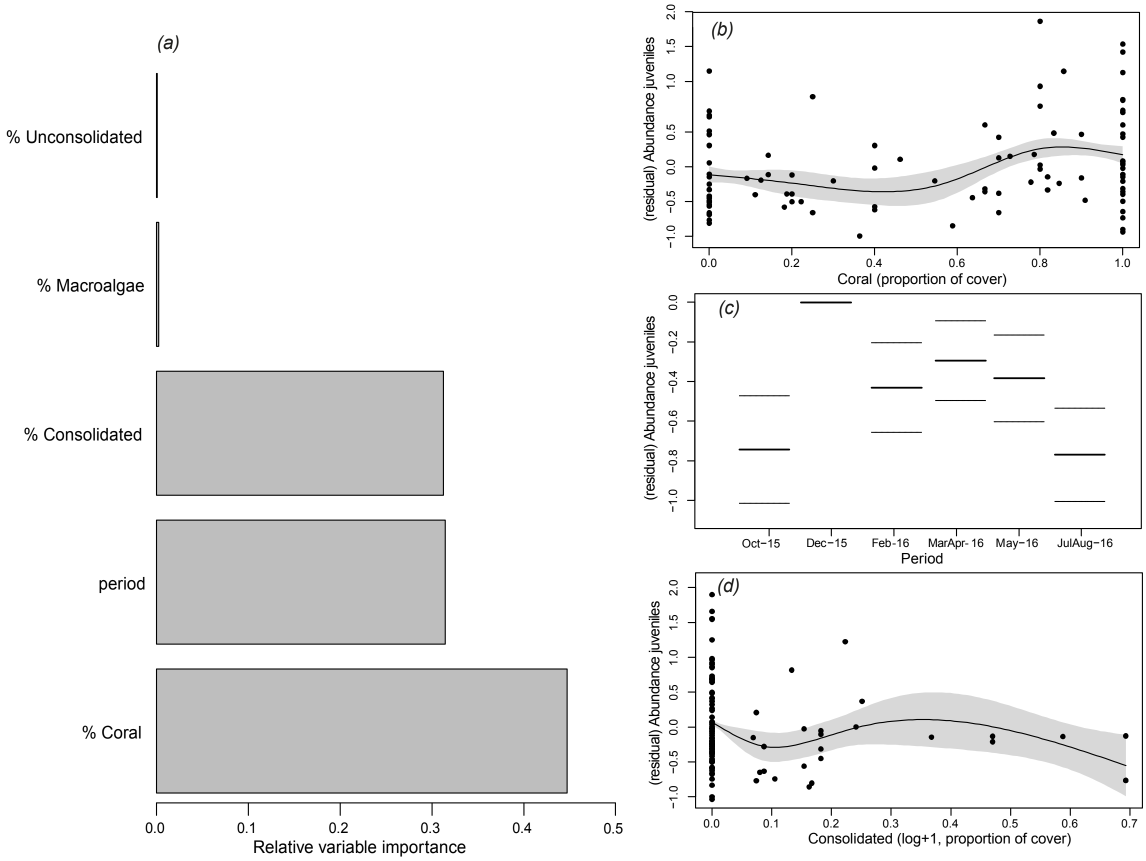

Figure 6. Graphical representation of the most parsimonious generalised additive mixed model (GAMM) for explaining variation in total abundance of juvenile fishes according to habitat (% or proportion of cover) and sampling period; (a) shows relative variable importance for all explanatory variables used in the full subset of fitted GAMMs; (b), (c) and (d) show residual abundance of total juvenile fishes in response to their most important explanatory variables presented in order of importance (see Table 3 for model selection criteria). Solid black lines represent model fit (estimated smoothing curve for continuous variables), and shading (b and d) or dotted lines (c) represent ± 2*SE of the model fit estimate. *Note there is no SE associated with the December period in (c), because this was taken as the reference level for factor period by the model.

Table 4. Output from the best univariate (GAMMs; *a*) and multivariate (DistLMs, *b*) models, selected from the full subset of fitted models for predicting total abundance of juvenile fishes in coral reefs in the southern Kimberley region in response to habitat and sampling period. In (*a*) the five best GAMMs are presented and in (*b*) all DistLMs within 2 AICc units of each other. The final models selected were the ones with the lowest Akaike Information Criterion value corrected for finite sample sizes (AICc), and with the fewest variables (most parsimonious; in bold).

Dependent variable	Explanatory Variables	edf	R^2	AICc
Juvenile MaxN bi-monthly data coral habitat (# fish per RUV)				
(*a*) GAMMs	**Consolidated, coral, period**	**16.42**	**0.447**	**746.784**
	Coral, period	13.23	0.410	757.378
	Consolidated, macroalgae, period	15.69	0.425	757.429
	Coral, unconsolidated, period	14.20	0.412	759.284
	Consolidated, unconsolidated, period	13.57	0.396	766.243
(*b*) DistLMs	Macroalgae, period		0.145	746.900
	Coral, period		0.138	747.800
	Macroalgae, unconsolidated, period		0.155	748.140
	Macroalgae		0.037	748.400
	Period		**0.113**	**748.570**
	Consolidated, algae, period		0.151	748.600
	Consolidated, coral, period		0.150	748.700
	Macroalgae, coral, period		0.150	748.720
	Coral, unconsolidated, period		0.149	748.890

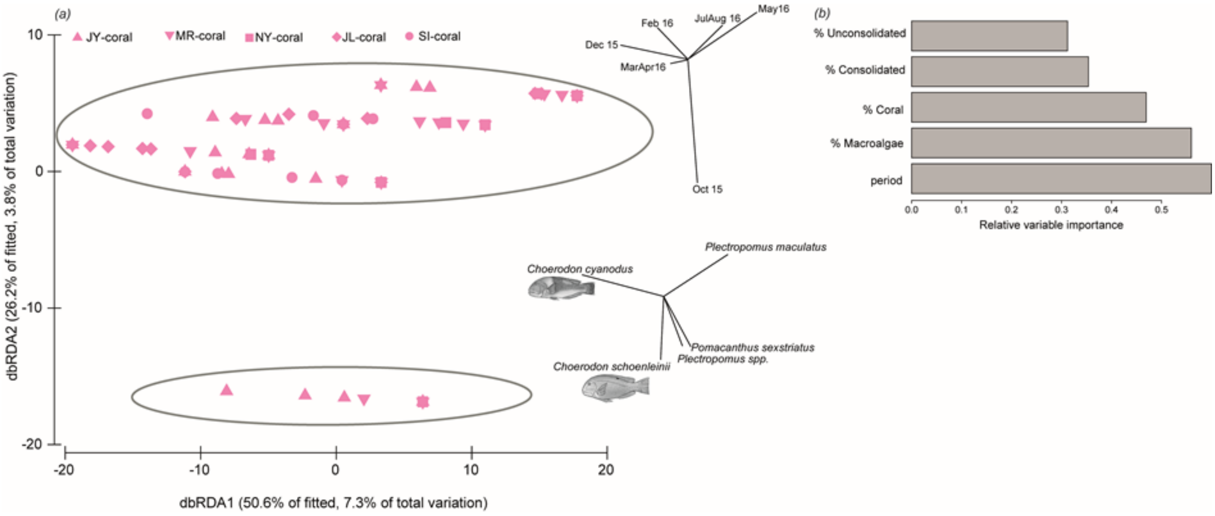

Figure 7. Distance based redundancy analyses (dBRDA) showing variation in juvenile species assemblages (bottom right vectors) in coral reef habitat according to sampling period (top right vectors) (a). Data are MaxN per RUV replicate plotted at the site level and represented by symbols in the legend. Relative variable importance values for all explanatory variables in the full subset of fitted distance-based linear models (DistLMs) are shown in (b); for model selection see Table 4. Circles depict the two major clusters visually identified, and have no statistical significance.

3.4 Abundance and size-structure patterns of the ten most abundant juvenile fish species

Species-specific abundances between wet and dry seasons in the ten most abundant species show that recruitment strength is typically higher in the wet season (Figure 8a). Higher wet season recruitment was more pronounced in some species, such as *Gerres oyena*, *Siganus lineatus* (both seagrass associated), and *Scarus ghobban* (coral-algae associated) (Figures 5 and 8a). In contrast, species such as *Choerodon cyanodus* and *Lutjanus carponotatus* show considerably less differences between wet and dry seasons indicating the potential for year-round recruitment (Figure 8a). A more detailed analysis of species-specific abundance patterns across bi-monthly surveys (coral habitat only) generally agreed with these seasonal patterns. Seven of the top ten most abundant species showed higher recruitment during wet season months (December to April, Figure 8b to f, and k). In stark contrast, three species (*Dischistodus darwiniensis*, *Choerodon schoenleinii*, *Plectropomus maculatus* (biindarral) and *Chaetodon aureofasciatus* (roola)) recruited in higher numbers during the dry season months (Figure 8g to j).

Length-frequency distributions highlighted the seasonal and bi-monthly differences in juvenile fish abundance patterns, and allowed us to assess recruitment more directly by looking at patterns in the smaller juvenile size classes for four species with a good representation of length measurements (Figure 9). A clear recruitment pulse was identified for *Choerodon cyanodus* (igoolan) during March and April (end of the wet season), although some level of recruitment was present throughout the year (Figure 9a). *Lutjanus carponotatus* (joorloo) showed the strongest evidence of recruitment during October (end of the dry season) although a second, weaker recruitment pulse was observed during March and April (Figure 9b). Both *Scarus* species showed evidence of recruitment throughout the year with no clear recruitment pulses detected (Figure 9c and d).

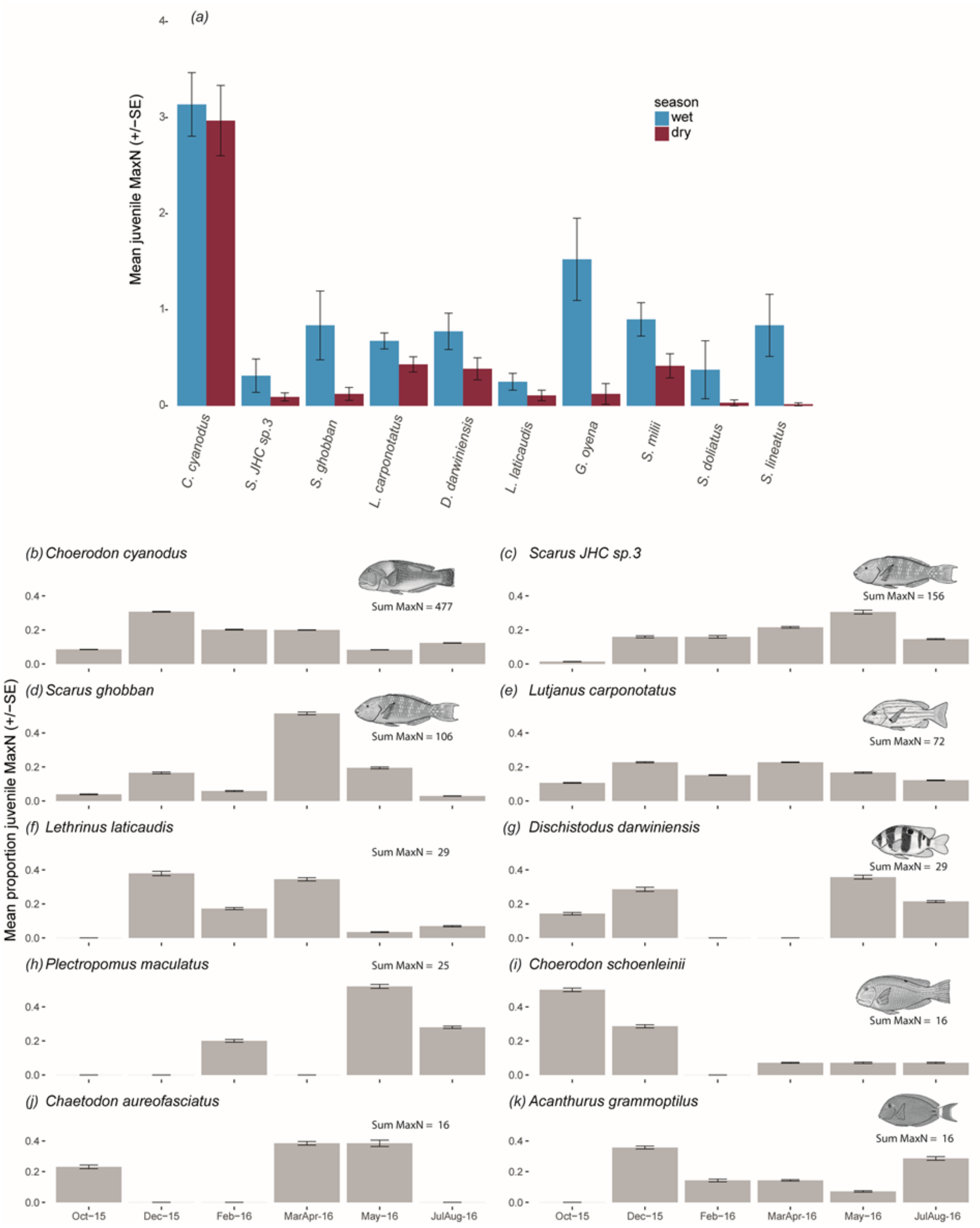

Figure 8. Average juvenile abundance (MaxN ±SE) for the ten most abundant fish species in all habitats surveyed across wet and dry seasons (a), and proportion of total abundance per sampling period for the ten most abundant species found in coral reef habitat (b to k). Fish images are included for species that were the most important in discriminating juvenile fish assemblage structure across habitats sampled (see Figures 6 and 7). Sum MaxN represents the total number of fish identified in coral reef RUVs across the six time periods surveyed.

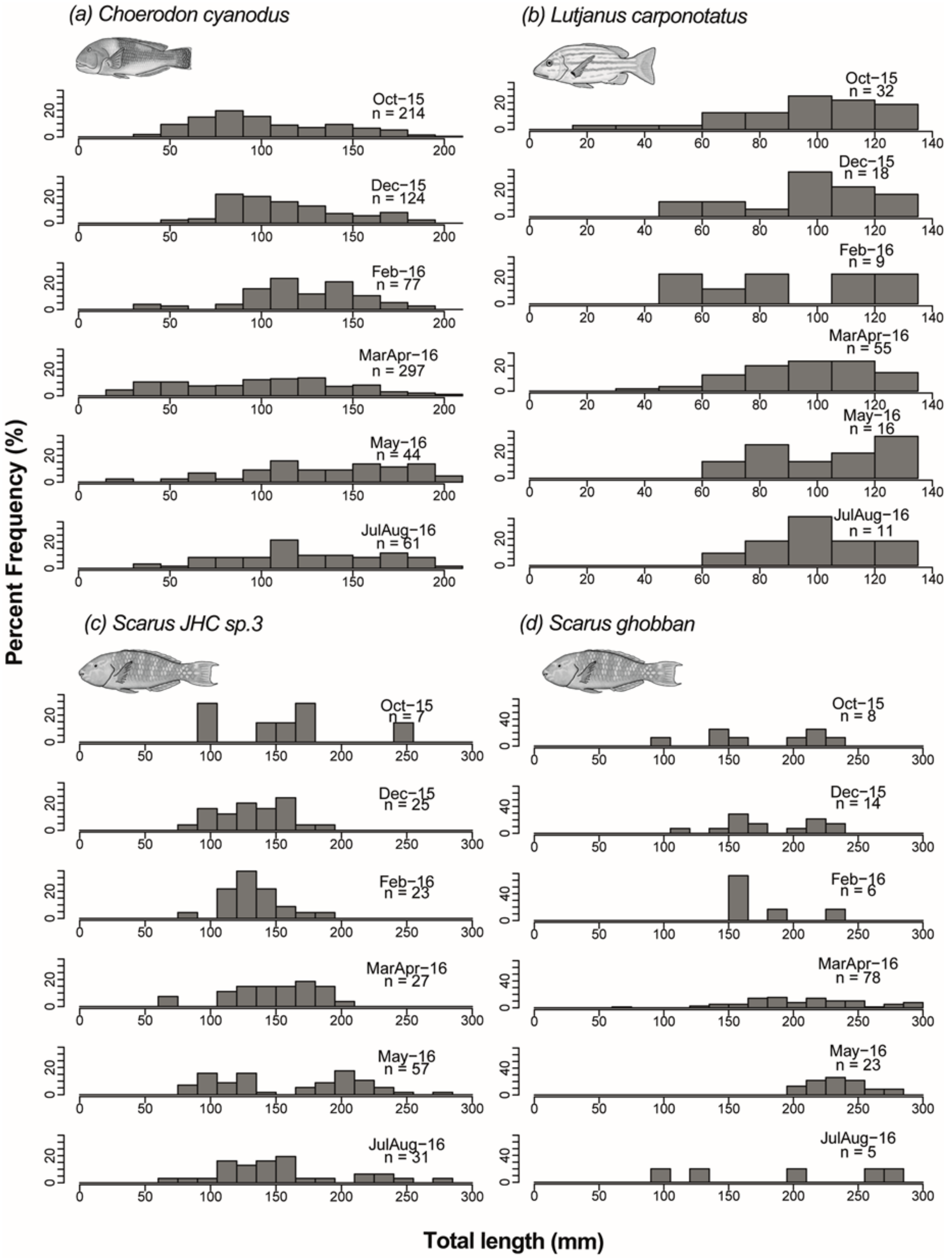

Figure 9. Length-frequency distributions according to the six bi-monthly periods surveyed for four species for which length data were best represented throughout the year (a-d); shown are percent frequencies according to selected bins based on maximum juvenile total length (L_T); n = sample size. Note the different scales along the *Y*-axis for *Scarus ghobban.* Length-frequency data represent length measurements gathered at all habitats surveyed; note that Dec-15, Feb-16, May-16 and JulAug-16 contain only coral reef data.

3.5 Species accumulation curves and sampling effort

The accumulation of species with increasing sampling effort (no. of RUVs) showed no asymptote at any level of sampling suggesting that some latent diversity remains in all habitats (Figure 10). Among habitats, sampling effort produced fairly similar numbers of species (Figure 10a, Appendix 3). Coral habitats recorded the highest species diversity followed by seagrass habitats (Figure 10a, Appendix 3). Similarly, species accumulation curves between wet and dry seasons showed no real marked point at which it was obvious that replication is sufficient to encompass >90% of overall diversity (Figure 10b). Sampling effort produced similar numbers of species between seasons, with slightly higher number of species recorded during the wet season (Figure 10b, Appendix 4).

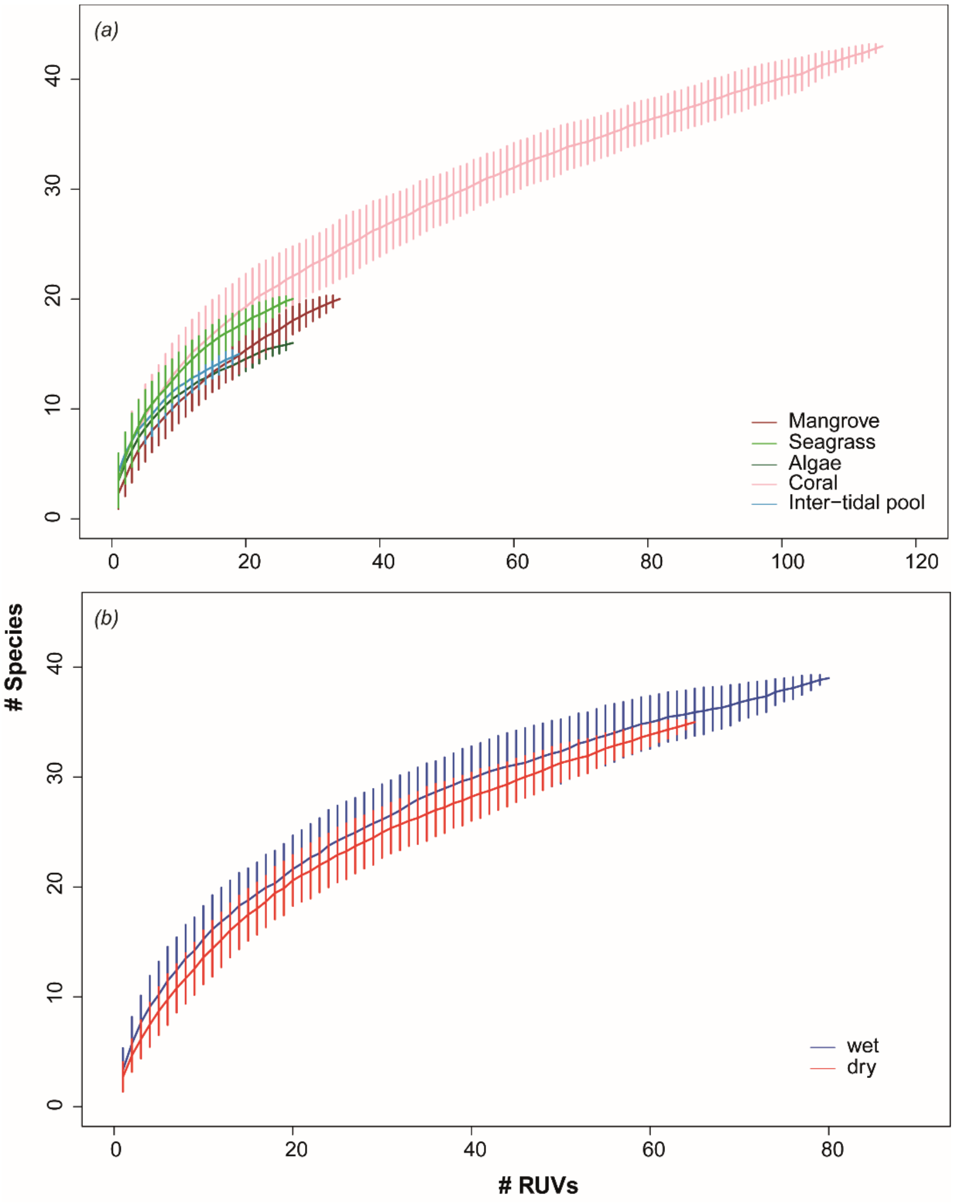

Figure 10. Species accumulation curves showing the number of unique species identified according to the number of RUV samples obtained at each of the five main habitats sampled (mangrove, seagrass, algae, coral and inter-tidal rockpools; a), and wet *vs.* dry seasons (b).

4 Discussion and Conclusions

This study has documented the spatial and temporal patterns of fish recruitment in the Cygnet Bay and Sunday Island group and addressed several key objectives:

1. *Develop cost-effective techniques suitable to the Kimberley marine region that, wherever possible, allow direct comparisons with other data-sets in Western Australia*

We identified and developed stereo remote underwater video systems (stereo-RUVs) to optimally survey and monitor fish recruitment at the different shallow water habitats identified in the western Kimberley. Specific camera requirements and design for sampling small fish recruits with this baitless stereo-video method are described in methods section 2.2. Stereo-RUVs were suitable for deployment at all habitats safely (without divers), were repeatable, provided a permanent record, and could be easily deployed in a reasonable timeframe. Our trials further indicated that stereo-RUVs were efficient in providing precise estimates of abundance and acceptable levels of diversity, when compared to the eight other techniques trialed (*i.e.* rotenone, box trawls, drop cameras, underwater visual census (transect, stationary and block), patch reefs and pearling panels; see Depczynski et al. 2015). A potential downside of the method is the post processing time needed for video analyses after initial data collection, but this time can be reduced considerably by focusing on the most abundant and representative species recruiting to the region (see objective 2 below). We recommend this focused approach to video analyses for future recruitment monitoring in the Kimberley via stereo-RUVs.

It is important to note that the deployment of RUVs requires reasonably clear waters and is highly dependent on tides in the Kimberley region. This study was conducted in a relatively clear region of the western Kimberley, after careful consideration of the local tidal regimes. Extension of these sampling methods to areas further east in the Kimberley which are typically turbid, will require previous evaluation of local conditions to determine feasibility. This will be crucial for direct comparisons between similar datasets for the region, given that the estimates for abundance from stereo-video techniques are based on the conservative measure of MaxN. Therefore, comparison with recruitment estimates from other methods may not be appropriate.

2. *Provide baseline quantitative information on levels of fish recruitment across a gradient of commonly available Kimberley habitats*

Remote underwater video was moderately successful in revealing fish recruitment in the study area, with recruits detected in more than 40% of all species recorded in the RUVs, allowing us to gather baseline quantitative information of recruitment at five different shallow water habitats: mangroves, seagrass, algae, coral reefs and inter-tidal rockpools. However, detected abundance of recruits was very low for most species, with 88% of total juvenile abundance contributed by only 12 species, and 39% of total juvenile abundance represented by a single species - *Choerodon cyanodus* (igoolan). Note that many of these 12 species are those of greatest importance to the Bardi Jawi community in terms of diet and cultural significance (see results section 3.1). The reasons for this generally low detected diversity and abundance are not known, but a combination of variables may be responsible including environmental, seasonal, biological/behavioural and methodological. For example, strong tidal fluxes in the region, together with high input of sediments and low salinity may affect larval connectivity and survival (Holliday et al. 2011). The Sunday Strait, directly to the east of the Sunday Island Group, has been found to be a potentially important barrier to larval dispersal, at least in some species (Berry et al. 2016). In addition, although deemed to be the most versatile and safest monitoring method across all habitats in the area (Depczynski et al. 2015), the capacity for RUVs to detect fish recruits is limited by factors such as water visibility and the cryptic nature of many juvenile fishes, including those that bury under soft sediments (*e.g.* wrasse Choat & Bellwood 1998). Therefore, recruits might be difficult to detect, especially in weed or mangrove habitats (Wilson et al. 2010, Evans et al. 2014) or recruit to deeper areas offshore. Finally, during 2016 water temperatures were extremely high with the hottest sea surface temperate anomalies on record, resulting in widespread coral bleaching in northern Australia (Bureau of Meteorology 2017); this is likely to have impacted fish recruitment and survival (*e.g.* Pankhurst & Munday 2011), potentially leading to underestimates of typical recruit abundance in Cygnet Bay and the Sunday Island group. Furthermore, interannual variability in recruitment is typically very high (Doherty 1991, Sampey et al. 2004, Trip et al. 2014). For these reasons, future monitoring to examine recruitment processes in more detail, assess interannual variability and responses to local environmental drivers, is suggested.

3. *Examine seasonal trends in fish recruitment for selected important species*

Recruitment was strongest during the wet season across all habitats and for nearly all species, although there is evidence for some level of recruitment during both seasons for at least some species (*e.g. Choerodon cyanodus*). Warm water temperatures are known to promote gonad development, larval growth and survival (Takahashi et al. 2012) and where seasonal differences in light and temperature are pronounced (*e.g.* subtropical and temperate seas) fish typically recruit during the summer months (Wilson et al. 2010, Cure et al. 2015). Although seasonal differences in sea temperature in the Kimberley are generally small (~2 ^{0}C, Ivey et al. 2016), these might still promote greater recruitment and survival during the warmer water months of the wet season (November to April). In addition, higher freshwater input during the wet season could increase the quantity of planktonic food available for fish recruits to feed on (De Robertis et al. 2003).

Unsurprisingly, our results also suggest that season is unlikely to be an exclusive driver of patterns in recruitment. Models that incorporate both season and habitat provided the strongest predictor of recruitment. This is expected because, among other things, habitats change from season to season (see point 4 below), and also because the influence of seasonal patterns are more evident in some habitats than others. Species-specific patterns also need to be taken into consideration, with some species apparently recruiting in only one season and/or a single habitat.

Our results appear to correlate strongly with traditional fishing knowledge and management. Some of the species considered most important to the Bardi Jawi community (e.g. *Acanthurus grammoptilis*, *Choerodon cyanodus*, *Lutjanus carponotatus*) are species that we have identified as having year round recruitment. These species are the mainstay of Bardi Jawi fishing and the community recognises that they can harvest year round without adversely affecting stocks (Smith 1997). There are exceptions. Some species of cultural significance to the Bardi Jawi community recruit most strongly in the wet season. For example, one of the most sought after species, *Siganus lineatus* (barrbal), is mostly targeted when they are 'fat' during the dry season (Smith 1997). This is during reproductive quiescence, when the fish accumulate fat stores in preparation for the next spawning season and are expected to hold higher levels of nutrients. While fish with more fat are more desirable, discussions with members of the Bardi Jawi community (see acknowledgements) demonstrate that this is also a deliberate method of avoiding the spawning season and conserving local fish stocks (see Rouja et al. 2003).

4. *Determine the relative importance of representative habitats to fish recruitment processes*

We identified aspects of both habitats and locations that promote juvenile fish diversity in the Kimberley region. The presence of a variety of coastal habitats in close proximity to each other creates a mosaic of recruitment habitats, food resources and environmental conditions, which allow species with different ecological requirements to successfully settle into the region. Furthermore, the presence of areas with high coral cover clearly promotes a greater abundance and species richness of juvenile fishes, as well as intermediate levels of consolidated substrates such as bedrock and boulders.

Different habitats clearly provide for different fish recruitment patterns, both in terms of species composition and abundance. Although some habitats tend to have higher abundance and diversity of fish recruits, there are differences in the type of fish that recruit to these habitats. For example, although mangroves and seagrass beds have lower diversity than coral reefs, some of the species important for local Bardi Jawi and recreational fisheries appear to recruit exclusively to just one of these habitats (*e.g. Lutjanus argentimaculatus* (maarrarn) to mangrove, and *Siganus lineatus* (barrbal) to seagrass beds). Therefore, conservation planning needs to recognize that all these habitats contribute to the overall pool and diversity of the Kimberley's fish fauna, are potential nurseries and warrant some level of protection, particularly to ensure sustainability of local fisheries resources.

However, the similarity in species assemblages and total juvenile abundance between algae, coral and intertidal rockpool habitats, suggests that these habitats can be united as one sampling unit of coral-macroalgal reef. This united sampling unit is complex because it represents a spatial mosaic of dominant benthic cover as well as a seasonally temporal continuum of algal cover associated to growth and senescence life history patterns. This united habitat would be ideal for monitoring recruitment strength because several of the most abundant and fishery-important species in the region are best represented here (*e.g. Choerodon cyanodus* (igoolan)*, Lutjanus carponotatus* (joorloo)).

5. *Assess possible biodiversity hotspots and population strongholds for juvenile fishes*

We were able to identify which aspects of locations and habitats promote species diversity, but weren't able to determine particular locations which could be considered a biodiversity hotspot. One of the reasons behind this is that sampling limitations didn't allow us to survey all habitats evenly at all locations, and therefore a comparison of diversity and abundance patterns according to locations was not appropriate. Nonetheless, our findings suggest that season and habitat differences are the most important indicators of juvenile fish diversity and abundance and that some level of protection of nursery grounds from different habitat types particularly during the wet season, would be ideal for the conservation of biodiversity and juvenile fish populations at the location level. Our analyses indicate that these factors (habitat and season), are more important than just location as determinants of juvenile recruitment patterns.

6. *Implications for future monitoring studies*

We have established initial monitoring sites for juvenile fish recruitment in representative habitats to form the basis for future long-term monitoring in the southern Kimberley region, and provided baseline data including species important for local and artisanal fisheries. Ideally, greater replication and complete replicate blocks would allow a better comparison between locations and habitats (see Table 1). However, sampling in the Kimberley is challenging due to strong tides and low visibility and deployment and retrieval of equipment is often limited to small windows of time, or delayed for extended periods.

Comparison of the seasonal and bi-monthly RUV datasets indicated that sampling during the end of the wet (March-April) and dry seasons (October) was appropriate for capturing temporal variation in recruitment. However, any future monitoring of fish recruitment should be concentrated during the wet season when abundances are at their maximum across nearshore habitats in the Kimberley region.

The spatial and temporal variability of the united sampling unit of 'coral-macroalgal reef' necessitates treating this as a continuous variable rather than a categorical one. The implication of this is that a stereo-RUV unit can effectively be dropped anywhere in this habitat at any time with no *a priori* expectation of the dominant habitat type because it can be quantified from the video *a posteriori*. This simplifies future monitoring in this particular habitat mosaic and requires less expertise or habitat appraisal by the team deploying the RUVs.

Remote underwater video (RUV) was the most appropriate for the region, as determined by a pilot study (Depczynski et al. 2015). However, accurate identifications are the basis of most biological and ecological studies and this is not always possibly with remote video techniques, particularly where individuals are small in size (*e.g.* juveniles), closely related species are visually very similar and visibility is low. While every care was taken to correctly identify individuals in the present study, the relatively high number of ambiguous identifications (*e.g.* to sp. or spp.; Appendix 2) demonstrates the limitation of this method. In saying that, the twelve species responsible for driving separation between habitats, as determined by the dBRDA analysis, are all generally easy to identify from video and confidence in our identifications of these species is high. Future video-based fish recruitment monitoring in the region should focus on these important and identifiable species to streamline efforts.

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