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The distribution of shallow marine fishes of the Kimberley, Western Australia, based on a long-term dataset and multiple methods

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ABSTRACT – The Kimberley and offshore marine waters of Western Australia are some of the least impacted environments in the world. The region is facing increasing pressure from anthropogenic stressors and there is a need to understand the baseline faunal communities. Fish surveys were conducted between 2009 and 2014, using a variety of methods, including UVC and extractive techniques. The results of these contemporary surveys were added to all known shallow water fish records from more than 100 years of historical museum databases. We present the first comprehensive species by site table, based on nearly 15,000 species records to summarise species presence at more than 134 unique locations across the Kimberley marine region and highlight new distributional records. This reference dataset of 1,529 species should inform managers and assist the development of representative marine protected areas.

KEYWORDS: biodiversity, museum, collections, UVC, inventory

INTRODUCTION

Most tropical marine ecosystems are already substantially impacted by human activities (Pyke and Ehrlich 2010) and all are facing increasing threats from anthropogenic pressures such as pollution, overfishing or global warming along with severe natural disturbances such as cyclones (Pauly 1995; Knowlton and Jackson 2008). Accurate species inventories can provide baseline data to monitor the effects of many of these concerns (e.g. Perry et al. 2005; Vergés et al. 2014). Furthermore, as one of the most fundamental components of biodiversity science, accurate species inventories reveal regional taxonomic breadth and define species distributions, uncovering patterns of community composition, hotspots, endemism and are central to broader issues of evolution, ecology and management (e.g. Hutchins 2001; Pyke and Ehrlich 2010; Briggs and Bowen 2013; Gaither and Rocha 2013).

Species inventories are often fit-for-purpose and methodological compromises must be made.

Most monitoring surveys are necessarily based on carefully standardised, statistically rigorous methods that reduce bias. Such approaches may provide a robust assessment of a subset of the total fish community (Samoilys and Carlos 2000; Usseglio 2015; Caldwell et al. 2016); however, such surveys rarely attempt to include cryptic or small species and often do not (or cannot) discriminate between morphologically similar species (Smith-Vaniz et al. 2006; Holmes et al. 2013), and are seldom conducted by taxonomic specialists. As a result most ecological methods, such as Underwater Visual Census (UVC) or Baited Remote Underwater Video System (BRUVS), will considerably under-detect, and hence under-estimate total biodiversity (e.g. Plaisance et al. 2011; Usseglio 2015). In contrast, ad hoc collections and observations compiled using multiple methods, over a long timeframe, and with confirmed voucher specimens often provide a more thorough species list. With cryptic, rare and extra-limital records specifically targeted, and identifications made by specialist taxonomists, such inventories can be among the most complete

(e.g. Johnson 2010; Larson et al. 2013; Moore et al. 2014; Roberts et al. 2019); however, data are usually collected in such a way that is difficult to use with the quantitative rigour demanded in most ecological studies (Caldwell et al. 2016).

Museums and other collection-based natural history research agencies are uniquely placed to provide the most comprehensive species inventories, employing dedicated taxonomists with honed identification skills backed by extensive collections of verifiable voucher specimens collected over many decades and by a diversity of methods. The importance of such taxonomic precision is often overlooked (Bortolus 2008). In an attempt to compile a 'complete' species inventory, Moore et al. (2014) summarised historical museum records (vouchers and observations between 1880 and 2009) of shallow water marine fishes from the Kimberley, north-western Australia and reported that 1,475 species were currently confirmed from shallow (<30 m) inshore and offshore reefs of the region.

The Kimberley and offshore areas comprise a vast expanse of remote marine environments with an incredible diversity of habitats and associated faunas (Wilson 2013; Wilson 2014; Jones et al. 2017). Inshore fringing reefs in the region are subject to enormous tides (>11 m), high turbidity and relatively low wave energy (DEC 2009; Wilson 2014). In contrast, the offshore reefs of submerged midshelf shoals and continental edge atolls of the region are typical Indo-west Pacific coral reef environments of relatively clear water and low productivity, and subject to seasonal cyclonic activity (Wilson 2013).

The shallow water reefs of the Kimberley are among the least impacted in the world by virtue of their remote location and low human population density (Halpern et al. 2008). Despite this, the region has a history of traditional, recreational and commercial fishing (Nowara and Newman 1996; Fox 1998; Molony et al. 2011), oil and gas exploration and extraction (Moore et al. 2016) and is increasingly affected by rising sea temperatures and coral bleaching (Ceccarelli et al. 2011; Gilmour et al. 2013; Le Nohaïc et al. 2017; Richards et al. 2019). Parts of the Kimberley marine region have been designated as marine protected areas for decades (e.g. Rowley Shoals), several years (e.g. Camden Sound) or are soon to be (e.g. Buccaneer Archipelago). Furthermore, since 2011 inshore areas of the region have been progressively designated as Indigenous Protected Areas recognising traditional custodianship of Sea Country and supporting joint management of environmental, biodiversity and cultural values (Kimberley Land Council 2019). Despite the known biological significance of the region, including decades of research, the

marine flora and fauna of the Kimberley is still inadequately documented; largely due to the vast area, remoteness and environmental challenges of working there.

Here we report on six years of baseline marine surveys in the Kimberley between 2009 and 2014, which builds on a list of shallow water fish records from more than 100 years of historical records (Moore et al. 2014). We provide a comprehensive summary of known species presence at more than 134 unique locations across the Kimberley marine region and highlight new distributional records. This reference dataset should inform managers and assist the development of representative marine protected areas.

MATERIAL AND METHODS

Shallow water (<30 m) fishes were sampled with other phyla as part of the Western Australian Museum's (WAM) Kimberley Woodside Collection Project. Briefly, the 2009–2014 study area included reefs and islands near Cape Leveque in the south to Long Reef in the north and out to the continental edge atolls of the Rowley Shoals in the south, to Ashmore and Hibernia reefs in the north (see Bryce et al. 2018). The recent surveys included six 'Island Groups': three inshore (Buccaneer and Bonaparte archipelagos, Cassini Island/Long Reef), two offshore (Rowley Shoals and Ashmore/Hibernia reefs) and a series of midshelf reefs and shoals (Table 1, S1). Full details of the project and recent study sites were provided by Bryce et al. (2017) and Richards et al. (2018).

Fishes were recorded by several methods:

Subtidal. Underwater Visual Census (UVC) was the main method of survey, where fish were counted by two independent, experienced observers [SM & JJ at Adele Island and Montgomery Reef; GM & SM at all other locations] on SCUBA or snorkel over a 60 minute period, during which the divers swam from deep (maximum of 20 m) to shallow at each station. All fish within a 10 m wide belt were counted and some effort was allocated to including cryptic species during and after the time period. Counts were progressively recorded onto underwater slates and the quantitative analysis of these data will be presented elsewhere (Moore et al. in prep.). Where identification was uncertain, specimens were either collected (by hand, net or clove oil) or photographed for later confirmation. All species recorded beyond the transect belt or time period were also noted.

Intertidal. Intertidal stations were sampled using the ichthyocide rotenone in contained pools at

low tide. The dimensions and depths of the pools varied considerably depending on the geological structure of each reef, but sampling areas were usually in the order of 20–50 m². Pools were attended for at least one hour and all fishes were collected using hand nets. All specimens were later sorted on board the vessel and substantial voucher collections were retained and accessioned into the WAM fish collection.

Opportunistic. Additional species records were obtained by a variety of opportunistic methods. Angling was utilised sporadically, and other incidental sightings included landing on the deck (e.g. Hemiramphidae), dipnet from boat at night (e.g. Clupeidae), observed from the vessel (e.g. *Mobula*) or via substrate sampling for other invertebrate phyla (especially Gobiidae).

Identification of vouchered specimens and visual records were made by the authors, with input from other experienced ichthyologists with specific expertise. A conservative quality assessment process was followed whereby only those records identified with high confidence in the opinion of the authors were retained. All retained vouchers and photographs were identified in the laboratory, using available literature and comparison with specimens in museum collections. Currently accepted names generally follow the Australian Faunal Directory (ABRS 2019) with some decisions from Fricke et al. (2019). These recent records were added to a revised historical dataset of Kimberley marine fish fauna (summarised in Moore et al. 2014). The revisions to the data of Moore et al. (2014) reflect, inter alia, recent re-identifications, nomenclatural changes, improved knowledge and newly described species as well as incorporating additional data (Done et al. 1994; Fromont et al. 2012; Moore unpublished data). These combined data sources are presented as the first comprehensive species by site table for the Kimberley marine fishes.

RESULTS

RECENT SURVEYS

As part of the Woodside Collection project, the recent fish surveys included 174 survey stations at 37 islands/reefs across six Island Groups (Appendix 1; also Bryce et al. 2018). This included 124 UVC and 50 intertidal fish collections with many additional opportunistic observations and collections (see Methods). Some reefs were surveyed multiple times, others only once (Bryce et al. 2018). The recent dataset comprises

more than 6,800 species records including more than 5,800 vouchered specimens permanently accessioned into the WAM collection. Additional unpublished UVC and collections by the senior author around the Sunday Islands and Bonaparte Archipelago between 2014 and 2016 were also included in Appendix 1.

After quality assessment to remove tentatively or unidentified species, the recent surveys recorded 840 taxa, most of which have been identified to species (Table 1, S1). Hundreds of tentatively identified records were removed pending further research. However, 10 taxa identified only to genus or family were retained, either because no other representatives of that genus were recorded (e.g. *Rhynchobatus* sp.), the taxonomy of the group is known to be unresolved (e.g. many gobies) or identification is especially difficult (e.g. female Bythidae). We felt that there was value in including these incompletely identified records to the species by site table to note their presence and encourage further research interest.

The taxa recorded during the recent surveys represent 79 families, with the most speciose being Labridae (98 spp.), Gobiidae (86 spp.) and Pomacentridae (84 spp.) (Appendix 1). The species most widely recorded (not the most abundant) were *Labroides dimidiatus* (32 islands), *Acanthurus grammoptilus* (30 islands), *Thalassoma lunare* (30 islands), *Scarus schlegeli* (29 islands) and *Pomacanthus sexstriatus* (28 islands) (Appendix 1). Nearly 30% of taxa were only recorded using extractive collecting methods (clove oil, rotenone, angling, netting, etc.) and not detected by UVC (data not presented).

In general, species richness increased with decreasing latitude and distance from mainland Australia (Table 1). An average of 94 and 82 species were recorded at reefs within the Buccaneer and Bonaparte archipelagos in the southern and central Kimberley, respectively. The northern Kimberley reefs around Cassini Island and Long Reef supported an average of 207 species. The mid-shelf reefs averaged 107 species, while the Rowley Shoals averaged 315 species and Ashmore and Hibernia reefs averaged 337 species.

REVISED FULL KIMBERLEY DATASET

Following a similar quality filtering process, the full dataset now includes a total of 1,529 shallow water marine fish taxa from the Kimberley region based on nearly 15,000 species records (Appendix 1), which represents an increase of more than 50 species to the whole Kimberley over the most

recent species inventory (Moore et al. 2014; Table 2). New records of species were made at every recently surveyed island/reef, ranging from 11 new records from Wildcat Reefs in the Bonaparte Archipelago to 219 new records from the midshelf Browse Island (Table 1). Fourteen of these reefs were surveyed for the first time (although a single historic opportunistic record was known from both Albert Reef and Browse Island; Table 1). Substantial additional species records were added by the recent surveys at the level of Island Group, especially inshore (108–132 species added) and midshelf (273 species added) (Table 1). The new species records are generally dispersed across the

fish phylogeny although a quarter to a third of additions at each Island Group were cryptobenthic species (Appendix 1).

There are likely ten new species records for Western Australia, six of which are new species records for Australia (Table 2; but see Discussion). Four new species have been described, either directly or indirectly from specimens collected during this project: *Pseudopataecus carnatobarbatus* Johnson, 2012; *Plectorhinchus caeruleonothus* Johnson and Worthington Wilmer, 2015; *Neopomacentrus aktites* Allen, Moore and Allen, 2017; *Scolopsis meridiana* Nakamura, Russell, Moore and Motomura, 2018.

TABLE 1 Summary of fish species richness at recently surveyed islands and reefs in the Kimberley indicating historic (pre-2009) and recent (2009–2016) surveys.

	Historic	Recent	Total	Recent Additions
Buccaneer Archipelago				
Cygnet Bay/Sunday Islands	138	82	168	30
Brue Reef	0	117	117	117
Albert Reef	1	57	58	57
Adele Island	16	191	197	181
Fraser Island	0	86	86	86
Beagle Reef	87	93	133	46
Irvine & Bathurst Islands	41	42	69	28
Mavis Reef	0	96	96	96
King & Conway Islands	0	83	83	83
Total	273	274	381	108
Bonaparte Archipelago				
Champagne Island	0	73	73	73
Wildcat Reefs	66	36	77	11
Montgomery Reef	116	120	177	61
Black Rocks	0	67	67	67
White Island	21	122	126	105
De Freycinet Island	32	84	88	56
Hedley Island	24	83	91	67
Colbert Island	30	44	66	36
Woodward Island	43	43	76	33
Robroy Reefs	96	128	155	59
Maret Islands	34	81	99	65
Berthier Island	34	24	56	22
Heritage Reef	71	92	117	46
Montalivet Islands	70	123	144	74
Patricia Island	0	76	76	76

	Historic	Recent	Total	Recent Additions
Jamieson Reef	44	95	103	59
Condillac Island	0	101	101	101
Total	383	340	511	128
Cassini/Long				
Cassini Island	169	225	278	109
Long Reef	71	189	206	135
Total	188	270	320	132
Mid-Shelf Shoals				
Browse Island	1	220	220	219
Echuca Shoal	0	50	50	50
Heywood Shoal	0	90	90	90
Vulcan Shoal	0	78	78	78
Eugene McDermott Shoal	0	96	96	96
Total	1	274	274	273
Rowley Shoals				
Imperieuse Reef	142	330	346	204
Clerke Reef	486	317	559	73
Mermaid Reef	418	298	471	53
Total	605	423	685	80
Ashmore/ Cartier/ Hibernia				
Ashmore Reef	791	423	832	41
Hibernia Reef	345	252	438	93
Total	886	459	926	40
Kimberley Total	1470	840	1529	59

TABLE 2 New fish species records from recent Kimberley surveys. Species are additions to the list reported by Moore et al. (2014). New records for Western Australia and Australian waters are indicated.

Family	Species	Kimberley	Western Australia	Australia
Dasyatidae	<i>Pastinachus ater</i>	+		
Myliobatidae	<i>Aetomylaeus vespertilio</i>	+		
Muraenidae	<i>Echidna delicatulus</i>	+	+	+
Clupeidae	<i>Sardinella brachysoma</i>	+	+	
Syngnathidae	<i>Campichthys tricarinatus</i>	+		
Syngnathidae	<i>Lissocampus fatiloquus</i>	+		
Scorpaenidae	<i>Parascorpaena aurita</i>	+		
Aploactinidae	<i>Pseudopataecus carnatobarbatus</i>	+		
Plesiopidae	<i>Notograptus gregoryi</i>	+		
Apogonidae	<i>Ostorhinchus wassinki</i>	+		
Malacanthidae	<i>Hoplolatilus starcki</i>	+	+	
Carangidae	<i>Alepes vari</i>	+		

Family	Species	Kimberley	Western Australia	Australia
Carangidae	<i>Carangoides gymnostethus</i>	+		
Carangidae	<i>Decapterus macarellus</i>	+		
Carangidae	<i>Seriolina nigrofasciata</i>	+		
Caesionidae	<i>Pterocaesio chrysozona</i>	+		
Caesionidae	<i>Pterocaesio lativittata</i>	+	+	+
Caesionidae	<i>Pterocaesio marri</i>	+		
Haemulidae	<i>Diagramma melanacrum</i>	+	+	+
Lethrinidae	<i>Lethrinus amboinensis</i>	+		
Lethrinidae	<i>Lethrinus punctulatus*</i>	+		
Lethrinidae	<i>Lethrinus variegatus</i>	+		
Mullidae	<i>Upeneus asymmetricus</i>	+		
Chaetodontidae	<i>Chaetodon plebeius</i>	+		
Pomacentridae	<i>Neoglyphidodon thoracotaeniatus</i>	+	+	+
Labridae	<i>Leptoscarus vaigiensis</i>	+		
Labridae	<i>Scarus fuscocaudalis</i>	+	+	+
Labridae	<i>Xenojulis margaritaceus</i>	+		
Pinguipedidae	<i>Parapercis xanthozona</i>	+		
Blenniidae	<i>Blenniella bilitonensis</i>	+		
Gobiidae	<i>Amblyeleotris periophthalmus</i>	+		
Gobiidae	<i>Asterropteryx atripes</i>	+	+	+
Gobiidae	<i>Ctenogobiops mitodes</i>	+		
Gobiidae	<i>Eviota</i> cf. <i>fasciola</i>	+		
Gobiidae	<i>Eviota</i> cf. <i>nebulosa</i>	+		
Gobiidae	<i>Eviota</i> cf. <i>nigripinna</i>	+		
Gobiidae	<i>Eviota</i> cf. <i>sebreei</i>	+		
Gobiidae	<i>Fusigobius maximus</i>	+		
Gobiidae	<i>Fusigobius melacron</i>	+		
Gobiidae	<i>Gobiodon axillaris</i>	+		
Gobiidae	<i>Palutrus</i> sp.	+		
Gobiidae	<i>Priolepis inhaca</i>	+		
Gobiidae	<i>Trimma maiandros</i>	+		
Acanthuridae	<i>Acanthurus auranticavus</i>	+		
Acanthuridae	<i>Acanthurus leucocheilus</i>	+		
Acanthuridae	<i>Acanthurus maculiceps</i>	+	+	
Acanthuridae	<i>Naso fageni</i>	+		
Acanthuridae	<i>Paracanthurus hepatus</i>	+	+	
Scombridae	<i>Katsuwonus pelamis</i>	+		
Scombridae	<i>Thunnus obesus</i>	+		
Monacanthidae	<i>Acreichthys radiatus</i>	+		
Tetraodontidae	<i>Lagocephalus scleratus</i>	+		

* The true identity of this well-known species remains unresolved but this is the name most widely used.

DISCUSSION

The shallow marine reefs of the Kimberley Project Area support an incredible diversity of fishes, akin to the more recognised Great Barrier Reef World Heritage Area (Hoese et al. 2006). This is largely a result of the enormous area of coverage (~476,000 km²), its adjacency to the centre of tropical marine diversity (e.g. Gaither and Rocha 2013) and the diversity of habitats (Richards et al. 2018).

This incredibly rich fauna is variably distributed across the region. General biogeographic patterns among fish communities in the Kimberley region are recognised, with a considerably higher diversity in offshore regions and latitudinal effects in inshore areas (Hutchins 1999; Hutchins 2001; Travers et al. 2012, 2018; Moore et al. 2014). A quantified analysis of such patterns is beyond the scope of the present paper and dataset; however, a biogeographic and ecological analysis of patterns of reef fish diversity and distribution using standardised UVC data from this project is underway (Moore et al. in prep). That said, Table 1 clearly supports the view that offshore fish communities are diverse, relative to inshore, and, notwithstanding differences in survey effort and methods, indicates that variation exists across the inshore areas of the Kimberley.

The recent surveys added a substantial number of new species records to every visited reef, especially inshore. This demonstrates how poorly known the Kimberley fish fauna remains and the importance of continued biodiversity assessments in the region. Admittedly, some of the recent additions are species that were known from the region (e.g. *Lethrinus* spp.) but not formally captured by previous surveys used in the dataset of Moore et al. (2014) or were known west and east of the Kimberley and assumed to have a continuous distribution (e.g. *Campichthys tricarinatus*). Prior to these recent surveys most of the inshore reefs had only been sampled by dedicated taxonomists on fewer than five occasions and some only once or not at all (see Moore et al. 2014). Even during recent surveys, certain reefs were only visited once or a few times. Such limited sampling precludes generating meaningful species accumulation curves, but no doubt they would not have neared asymptote for most of the Kimberley reefs and the documented species richness at all reefs will continue to grow steadily with increased sampling effort. One significant contribution from the recent surveys was the first museum-based surveys of five midshelf reefs/shoals (Table 1, Mid-Shelf Shoals), recording 273 species. Other than a recent,

important BRUVS-based ecological study across a range of depths and habitats by Moore et al. (2017), these reefs had not previously been surveyed.

The recent surveys also highlight the importance of extractive collection methods to understand the true biodiversity of coral reef fishes. In this study, nearly 30% of all species were only recorded this way. Over the past few decades, UVC has been used extensively as a tool for assessing reef fish diversity and this is rapidly being replaced by remote sampling methods such as BRUVS (e.g. Moore et al. 2017; Langlois et al. 2018). Such methods clearly have an important role in understanding reef fish ecology, distribution and biogeography, which is why UVC was central to the present study and to previous museum-based biodiversity surveys in the region (Done et al. 1994; Hutchins 1995, 1996, 1997, 1998; Morrison and Hutchins 1997; Moore and Morrison 2009). However, our results again demonstrate that these ecological methods miss many cryptic and pelagic species and, in many cases, cannot discriminate between morphologically similar species, and should not be used on their own to assess the total biodiversity of a region. Cryptobenthic fishes are increasingly being recognised for the significant role they play in ecosystem function (e.g. Goatley et al. 2017; Brandl et al. 2018) yet, without dedicated effort many are impossible to detect without extractive methods (e.g. Ackerman 2000). Assessing total biodiversity requires a variety of approaches, including extractive methods and retention of voucher collections for examination by expert taxonomists. More recently, cryptic species (i.e. morphologically similar, as distinct from behaviourally cryptic) are being identified by an integrative approach using genetics, morphology and other attributes, thus extensive voucher material with associated high-quality tissue for DNA extraction is an essential addition building our understanding of the true diversity of the world. Taxonomic research on Kimberley fishes continues — there are many known new species from the region still to be formally described, and other species complexes that are yet to be resolved. Many of these uncertainties, along with other tentative or dubious records, have been excluded from Appendix 1 until identifications have been resolved or verified. Extensive tissue collections were made during this project to support such taxonomic work.

Other non-collection based data exist for some parts of the Kimberley Project Area (e.g. Kospartov et al. 2006; Travers et al. 2012; Moore et al. 2017; ALA 2019; RLS 2019 and extensive databases held

by other organisations and individuals). Many of these records are observations made by non-taxonomists that are not supported by available, verifiable vouchers or photographs. While we do not necessarily question the validity of all such records (although in some instances, we do), it is impossible to assess the veracity of these records with the same level of rigour applied to the included museum records and therefore we have not attempted to include them. Furthermore, some of these datasets include habitats other than shallow water reefs, such as soft-bottom or mesophotic. This paper also does not capture the knowledge of the Traditional Custodians, particularly in inshore areas, and we encourage future collaborations to share knowledge. We hope that future endeavours can formally confirm the identifications in these other data sources to expand this list of Kimberley marine fish fauna and fully understand the distributions of all species of fishes across the region. The resolution provided by this dataset is critical for understanding finer scale species distributions, which is central to the successful implementation of effective marine protected areas and sanctuary zones (Pyke and Ehrlich 2010; Moore et al. 2016).

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APPENDIX 1

Species by site table representing all records of shallow water fishes from the Kimberley used in this dataset. Sites are assembled into Island Groups, approximately arranged by latitude. H refers to a historical record collected pre-2009 (see Moore et al. 2014); R refers to a recent record collected during the 2009–2014 surveys (see Bryce et al. 2018).

An electronic version of this appendix is available to download here:
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