109–124 (2012) DOI: 10.18195/issn.0313-122x.81.2012.109-124

Biogeographic patterns of frogs of the Kimberley islands, Western Australia

Paul Doughty[1]*, Russell Palmer[2], Mark Cowan[2] and David J. Pearson[2]

[1] Department of Terrestrial Zoology, Western Australian Museum, Welshpool, Western Australia, 6106, Australia.

[2] Department of Environment and Conservation, Science Division, PO Box 51, Wanneroo, Western Australia, 6946, Australia.

* Corresponding author: paul.doughty@museum.wa.gov.au

ABSTRACT – The islands off the Kimberley coastline of northern Western Australia are among Australia's most isolated areas. To date, frogs of the Kimberley islands have been a particularly poorly surveyed group owing to the remoteness of the region and the need to conduct surveys during the summer wet season at night when frogs call and are most active. Here, we report on the results of a three-year survey of frogs on 22 Kimberley islands. We found several broad patterns such as the near-ubiquitous presence of three species on most islands (*Limnodynastes lignarius, Litoria staccato* and *Uperoleia borealis*), all of which breed in rocky creeks. In contrast, some species common on the mainland were largely absent from the islands (*Litoria bicolor*, ground hylids and medium to large burrowing species).

Insular assemblages of frogs along the Northern Kimberley coast are intrinsically interesting on account of their persistence on generally rocky islands, with a long dry season, and the retention of a range of ecologies present, including rocky creek associations and large climbing species. No new species were discovered, including any species found to be restricted to the islands. None of the recorded species are considered threatened, but the islands do harbour 10 endemic frogs of the Kimberley region. Potential threats to frogs on islands include the arrival of exotic species (e.g. Cane Toads), chytrid fungus and habitat destruction.

KEYWORDS: Cane Toad, conservation, island biogeography theory, land bridge islands

INTRODUCTION

The Kimberley region of Western Australia (WA) is home to approximately 40 species of frogs, and is a region of pronounced endemism within the Australian frog fauna (How and Cowan 2006; Slatyer et al. 2007; Tyler and Doughty 2009; Bowman et al. 2010; Powney et al. 2010; Doughty 2011). Some species are common and widely distributed in northern Australia, such as *Cyclorana australis*, *Litoria caerulea* and *Platyplectrum ornatum*, with ranges often extending from the Kimberley region beyond Cambridge Gulf, through the Top End (northern Northern Territory [NT]) and in to Queensland. In addition to wide-ranging tropical species, the Kimberley region and adjacent north-west NT have 10 endemic species, with seven of these only known from the Northern Kimberley biogeographic region.

The frogs of the Kimberley have diverse morphologies and ecologies and are a conspicuous part of the fauna in the wet season when they are easily observed and heard in the evenings. The genus *Litoria* is especially prominent, with 17 species present. This is a diverse group that includes tiny (*L. microbelos*; maximum size 17 mm snout-urostyle length) to massive (*L. splendida*; to 118 mm) climbing species; a group of five small to medium (20–60 mm) non-burrowing ground frogs (e.g. *L. nasuta* and *L. pallida*); and several species with strong habitat preferences for rocky creeks and rockholes (e.g. *L. coplandi* and *L. meiriana*). Another prominent group are the small-bodied (20–40 mm) burrowing species of *Uperoleia*, a large genus of 27 species across Australia with nine described species in the Kimberley. Frogs of the genus *Limnodynastes* are medium-sized (50–60 mm) species and include two wetland species and an endemic rock-dwelling species (*L. lignarius*). *Crinia* are small-bodied (20–30 mm) non-burrowing frogs, with *C. bilingua* being a ubiquitous grassland and wetland species, whereas the poorly-known *C. fimbriata* is a north-

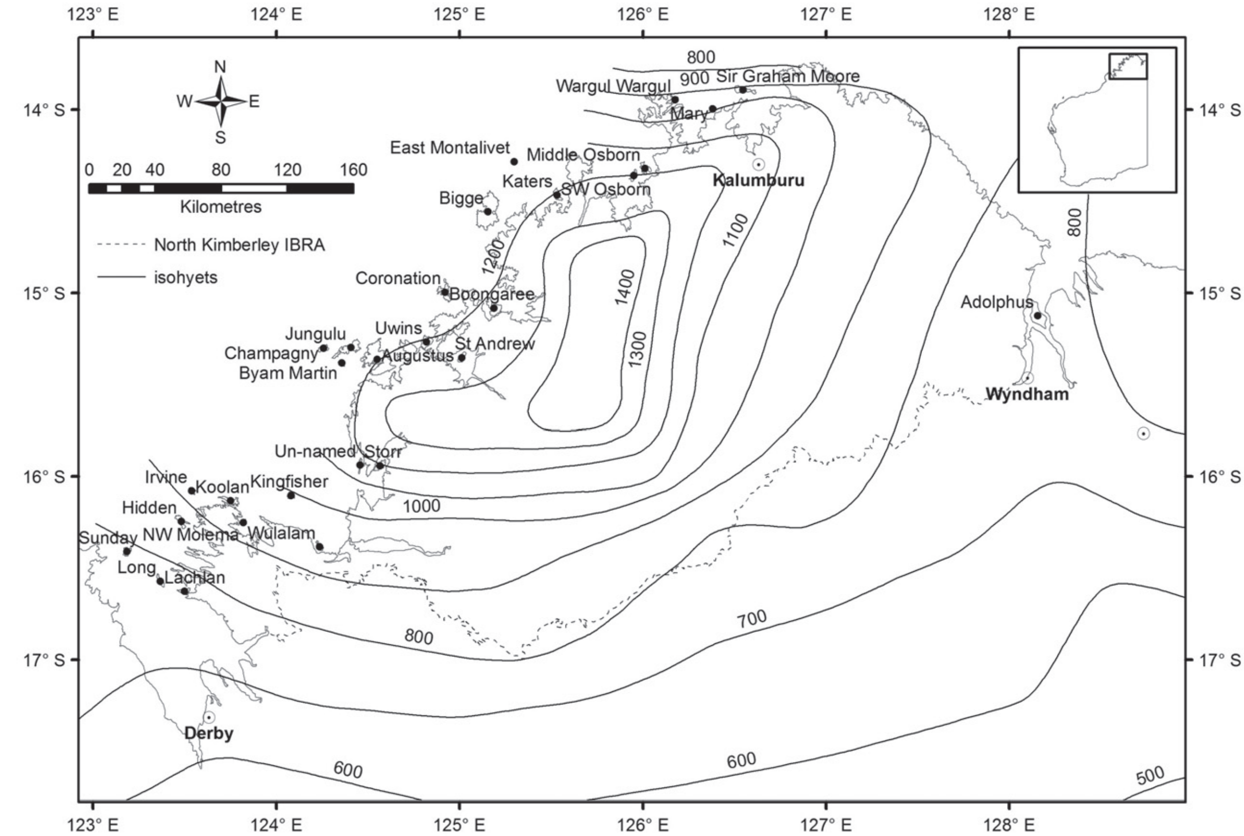

FIGURE 1 Map of the Kimberley region, Western Australia. Islands mentioned in the text are labelled. Rainfall isohyets are based on available meteorological data and rainfall projections from BIOCLIM. The Northern Kimberley IBRA region is also shown (broken line).

west Kimberley endemic associated with sandstone outcrops. Some arid species just reach the region to the south near Broome and the savannah country near Fitzroy Crossing (e.g. *Neobatrachus aquilonius*, *Notaden nichollsi* and *Uperoleia trachyderma*).

Historically, the frog fauna of the Kimberley islands has only been fleetingly sampled. Most previous vertebrate surveys of the islands have focussed on mammals, with surveys being conducted in the dry season for ease of logistics (e.g. Burbidge and McKenzie 1978; How et al. 2006). Since frogs are rarely seen or heard in the dry season of the northern monsoonal tropics (pers. obs.), collections or observations of frogs on previous surveys are best viewed as opportunistic.

The islands of the Kimberley are part of an ancient, submerged coastline (see Gibson and McKenzie 2012a). In island biogeography terms, the islands are 'land-bridge islands', formed by being separated from the mainland by rising sea levels (De Deckker and Yokoyama 2009). Under such circumstances, faunal communities are predicted to be depauperate relative to the mainland, as local extinction eliminates species from islands without opportunity for recolonisation (McArthur and Wilson 1967; Losos and Ricklefs 2010). Successful rafting of species to islands can occur but are expected to be uncommon events. In addition, some climbing species are known 'hitch-hikers' (e.g. *L. caerulea*, *Litoria rothii* and *L. rubella*) associated with human movements, especially with mining equipment and resort developments (Lever 2003). Islands off the Kimberley coast were formed approximately 8000 to 12,000 years ago (Nix and Kalma 1972). They are situated in an area subject to strongly seasonal rainfall, with the vast majority of rain falling in the wet season (December–March) (Figure 1).

The Kimberley island frogs face several challenges to survive and breed successfully. Islands are generally less diverse in habitat types and the extent of individual habitats than on adjacent mainland areas. In particular, areas with permanent free water or that retain year-round high soil moisture levels are rare due to generally skeletal or sandy soils and small catchment areas. Consequently, they are less likely to maintain moisture-loving species such as frogs over long periods. Frogs are considered to be poor rafters owing to their intolerance of salt water. However, when an island is close to the mainland or near the mouth of a large river, then colonization through rafting may be more likely.

To better understand the distribution of frogs on the islands, targeted short surveys were carried out over three wet seasons between 2008 and 2010 as a component of a larger biodiversity survey of selected Kimberley islands (Gibson and McKenzie 2012a). Here we report on the results of the frog survey which provides improved inventories for 22 of the islands sampled. Because frogs of the Kimberley have a diversity of morphologies and ecologies, we were able to explore what factors may contribute to their persistence on the islands. We conclude with comments on how our results can increase our understanding of the biota of these remote islands and discuss several conservation issues that pertain to frogs.

METHODS

ISLANDS SURVEYED

A summary of the goals and methods of the Kimberley Island Survey are outlined in greater detail in Gibson and McKenzie (2012a). We carried out night surveys on 22 islands during three wet seasons between 2008 and 2010. The wet season records were supplemented by some additional dry season collections. The largest Kimberley islands were selected as they were most likely to have a greater diversity of habitats and probably support more diverse vertebrate faunas (Gibson and McKenzie 2012a). To minimise transportation costs and for ease of logistics, islands were surveyed in groups from north to south along the coast. Helicopters and/or charter vessels were used during sampling to access the islands (Gibson and McKenzie 2012a).

Landing points to conduct frog surveys were selected based on their proximity to extensive flat areas where water could form pools and/or creeks and swamps if present. These areas were identified from satellite imagery available through Google Earth™. If a helicopter was transporting survey biologists to the island, then a short 10–20 min reconnaissance flight was usually taken to identify favourable areas for frogs and to determine walking routes from the drop-off point to survey sites.

SAMPLING METHODS

Surveying for tropical frogs, as with most frogs, is usually best accomplished during periods of high rainfall when males are calling; in this case during the wet season from December to March. In addition, as frogs are primarily nocturnal, it is most effective to survey them at night when they are active and usually calling. Recent rainfall, especially on the day of the survey and more generally in the days or weeks preceding the survey, resulted in increased frog calling activity and hence the ability to detect frogs. During the first two years of the survey, conditions were favourable for frog activity owing to good rains. In the third year when sampling the southern-most islands, the weather was drier with little rain falling during the sampling period.

Most islands were surveyed for only a single night for approximately 3–5 h. The larger islands had two survey sites that were sampled on two different nights. Sites were generally close to where dry season sampling for vertebrates had occurred the previous dry season (Gibson and McKenzie 2012a, 2012b). An attempt was made to cover as much area and as many habitats as possible while on the island, but this was restricted by the difficult rocky terrain and the time available. Survey teams usually had from one to four people, including at least one Traditional Owner.

Sites of potential free water such as creeks, rock platforms and wetlands (i.e. stands of *Pandanus*) where breeding choruses of frogs were likely to occur were identified from satellite imagery or during a helicopter reconnaissance. Some species did not reliably form breeding choruses (e.g. *Notaden weigeli* and *L. splendida*) but were often active after rains and were located by searching suitable habitat with head-torches. A digital audio recorder was carried on surveys as frog calls are species-specific and hence offer a reliable method of identification, especially for some cryptic taxa. Where possible, voucher samples (generally, a maximum of four males and one female, but usually fewer) of all species were taken from islands, preferably adult males whose calls had been recorded. All vouchered specimens were lodged at the WA Museum.

Tadpoles were collected from some islands and identified later by Marion Anstis, a tadpole specialist using published or unpublished data to identify key characters (e.g. Anstis 2002; Doughty and Anstis 2007; Doughty et al. 2009; Anstis et al. 2010). Molecular techniques were used to genotype some individuals (S. Donnellan, PD, RP, unpublished data).

We also made use of dry season surveys that targeted other faunal groups (Gibson and McKenzie 2012a) as well as historical records held by the WA Museum (e.g. Smith and Johnstone 1978). Five species were recorded during dry season surveys that were not detected in the wet. In one case, a photograph of *Litoria cavernicola* (care of I. Morris) and an old record of *L. rubella* were used to add these to the species recorded for Bigge Island. The combined dry season and historical records contributed a total of seven additional records with four species for Bigge Island, and one each for St Andrew, Sir Graham Moore and Storr islands.

DATA ANALYSIS AND INTERPRETATION

We treated all currently recognised taxa as full species, with one exception. The pair *Litoria aurifera* and *L. meiriana* were pooled in the analysis owing to their extreme phenotypic and behavioural similarity, although the two taxa possess different tadpole colouration and call components (Anstis et al. 2010) (both occurred on only one island). In addition, *Uperoleia borealis* is a complex of closely related species with the Northern Kimberley lineage distinct from other forms to the east (R. Catullo, PD, S. Keogh, unpublished data). Since only the Northern Kimberley form was encountered on the survey, here we refer to this lineage as simply *U. borealis*.

Our analysis is based on the recognition that a few species will have been missed by our surveys and assumes that data collected are adequate to undertake a useful analysis of assemblage structure. An increase in survey nights or habitats visited for diverse islands may yield species not detected by our surveys. As mentioned previously, the south-western islands were sampled in 2009 when low rainfall combined with their more southerly and already drier locations probably resulted in us not detecting some frog species and not detecting frogs at all on Wulalam, NW Molema, Kingfisher, Lachlan, Long and Sunday islands. We excluded Wargul Wargul and Mary from our analysis as no wet season sampling occurred on these islands, although frogs were detected on these islands during the dry season surveys (Appendix 1). Nevertheless, given the difficulty and cost in collecting any wet season data from these remote islands, we believe the data to be sufficiently informative to run at least preliminary analyses in a search for meaningful patterns of community assemblages. Furthermore, the analysis of our data can be used to guide further surveys to locate species that might be expected on some of the islands we sampled.

We used a multivariate statistical approach to identify frog community structure. The final analysis included 16 islands that we felt were adequately sampled for frogs. A similarity matrix for these islands based on frog species occurrence was produced using the resemblance routine in PRIMER v6 (Clarke and Gorley 2006). We used the Bray-Curtis distance association measure (i.e. the Sorensen association measure when occurrence data are used). Due to the sparseness of the sample matrix and the potential erratic behaviour of the Bray-Curtis measure in these circumstances, a dummy variable of '1' was added to all islands. At extremes this has the effect of dampening the response by ensuring samples with no content will be 100% similar and those with a single individual, whether the species is shared or not, now have some measure of similarity. Benefits of this technique are reviewed by Clark et al. (2006). The resultant association matrix was clustered using unweighted pair group method with arithmetic mean (UPGMA) and structures between samples were determined using the similarity profiling routine (SIMPROF) (Clarke and Gorley 2006). SIMPROF tests for evidence of structure in a set of samples and can be used to objectively define meaningful groups within a dendrogram. Clusters defined from the dendrogram were overlain on a non-metric multidimensional scaling ordination (nMDS) that has the advantage of preserving relative similarity distances between all data points (unlike dendrograms).

A matrix of island attributes, which incorporated both ordinal and quantitative environmental variables, including interpolated mean climatic variables derived from BIOCLIM (Houlder et al. 2000) was examined against the island association matrix using the BEST function in PRIMER. The BEST routine searches for individual and combinations of variables that produce the highest Spearman rank correlation with a sample-based association or resemblance matrix. Prior to this analysis, a Pearson correlation matrix for all environmental variables was calculated and where any pair of variables had a correlation of ≥0.8, one of the variables was excluded from the matrix. The final list of variables that were available for analysis is presented in Table 1. These data were normalised prior to analysis and the default settings of a maximum of five trial variables and the 10 best results was chosen in the BIOENV function. Statistical significance was tested using 99 trials in the permutation test.

Permutated species accumulation curves were produced in PRIMER using the islands as samples. The Chao 2 and Jacknife 2 species richness estimators were used as they are considered to give a meaningful view of species richness where only occurrence data are available (Magurran 2004).

RESULTS

SPECIES DIVERSITY

Table 2 shows the matrix of the 16 islands included in the community analyses presented below, and Appendix 1 shows additional records for Kimberley islands not included in our analysis. A total of 23 species were detected on these 16 islands. Table 3 lists these species and provides information on habitat preferences and breeding.

TABLE 1 Values of the Kimberley island environmental attributes used to examine frog assemblage associations.

Key: Area – area of island (log-transformed prior to analysis); Distance – distance to the mainland (log-transformed prior to analysis); Riparian – extent of riparian habitats (0 = no watercourses; 1 = some creeks; 2 = more creeks; 3 = numerous creeks); Boulder – extent of rock scree (0 = flat; 1 = rounded, soil-mantled hill slopes and plateaux, narrow scree; 2 = shallow joints, wide ledges, moderate scree; 3 = massive scree, deep joints and scarp country); 'Total # habitats' refers to how many of nine identified habitat types occur on the island (scree, massive boulder faces and cliffs, alluvial flats, volcanic slopes, rainforest, mangrove, beach sand, sandplain and riparian), estimated from aerial photographs; Elevation – maximum elevation; Rivermouth – proximity to river mouth (1 to 5 increasing distance from major river mouth); Rainfall – mean annual rainfall; mxTwmP – maximum temperature of the warmest period of the year; TwrmQ – mean temperature of the warmest 3-monthly period of the year.

Island	Area (ha)	Distance (km)	Riparian	Boulder	Total # habitats	Elevation (m)	Rivermouth	Rainfall (mm)	mxTwmP (°C)	TwrmQ (°C)
Adolphus	4134	1.96	2	2	4	244	1	827	37.55	31.05
Augustus	18,929	1.79	3	3	6	181	4	1170	34.17	29.13
Bigge	17,108	2.97	3	3	8	138	3	1103	34.63	29.23
Boongaree	4164	0.14	3	3	6	235	2	1138	35.31	29.03
Byam Martin	816	13.28	2	3	5	69	5	1144	33.58	29.04
Coronation	3791	6.07	1	2	7	153	5	1141	34.84	29.19
Hidden	1871	1.48	0	3	3	127	4	839	33.19	29.27
Jungulu	4803	18.91	2	3	5	95	5	1148	33.90	29.29
Katers	1713	1.4	1	3	6	101	4	1069	35.00	29.20
Middle Osborn	2378	2.34	3	2	6	240	4	1051	34.54	28.81
Sir Graham Moore	2812	2.84	2	1	7	61	4	979	34.40	29.50
St Andrew	1465	2.23	3	2	5	284	1	1127	35.66	29.48
Storr	1883	0.26	1	3	6	165	1	1007	35.40	29.90
SW Osborn	1340	3.07	2	3	6	134	4	1041	34.81	28.99
Un-named	897	0.69	1	2	6	83	3	1000	35.18	29.90
Uwins	3219	0.23	0	3	5	134	2	1155	34.81	29.11

TABLE 2 Frog species (grouped by family) occurrence for the 16 Kimberley islands surveyed that were included in the analysis. Island groups identified in the analysis of community assemblages are defined by shaded and non-shaded consecutive columns.

	Adolphus	Sir Graham Moore	SW Osborn	Augustus	Bigge	Boongaree	Byam Martin	Jungulu	Uwins	Storr	Un-named	Katers	Coronation	Middle Osborn	Hidden	St Andrew
Hylidae																
Cyclorana australis	+	+														+
Cyclorana longipes	+	+														
Litoria aurifera						+										
Litoria bicolor		+														
Litoria caerulea													+	+		+
Litoria cavernicola					+							+				
Litoria coplandi				+	+											
Litoria meiriana					+											
Litoria nasuta						+										
Litoria rothii						+				+						+
Litoria rubella	+	+			+											
Litoria splendida				+	+					+	+					
Litoria staccato	+			+	+	+	+	+	+	+	+	+				
Litoria watjulumensis				+	+	+										
Myobatrachidae																
Crinia bilingua				+	+											
Crinia fimbriata						+										
Uperoleia borealis				+	+	+	+	+	+	+	+	+	+		+	+
Uperoleia crassa		+	+													
Uperoleia lithomoda	+															
Uperoleia micra						+						+				
Limnodynastidae																
Limnodynastes lignarius	+	+	+	+		+		+	+	+	+	+				+
Notaden weigeli				+	+							+				
Platyplectrum ornatum	+	+														
TOTAL	7	7	2	8	10	9	2	3	3	5	4	6	2	1	1	5

FIGURE 2 Ordination (nMDS) of the 16 Kimberley islands included in the community assemblage analysis. Legend shows the four island groups identified in the SIMPROF analysis. (NB: SG Moore = Sir Graham Moore; and Jungulu and Uwins overlap)

Nearly all our records were additions to the known frog faunas of each island. The number of species occurring on islands ranged from 0–10, with the largest islands generally having the most species. Species richness was highest on Bigge Island (10 species), followed by Boongaree (9), Augustus (8) and Adolphus and Sir Graham Moore islands (7 each). In contrast, there were few frogs encountered on the nine southern-most islands in the third year of the survey, most likely due to the lack of rainfall immediately before and during the survey period. All but three of these southern islands were omitted from the final models, as no frogs were recorded (Figure 3).

A strong pattern to emerge was that three species occurred on most of the islands surveyed (Table 2): *L. lignarius* (11 of 16 islands included in the analysis, in addition to three islands we did not survey – see Appendix 1), *Litoria staccato* (10) and *U. borealis* (12). *Litoria splendida* was recorded from four islands. Species that were recorded from three islands were *Cyclorana australis*, *L. caerulea*, *L. rothii*, *L. rubella*, *Litoria watjulumensis* and *N. weigeli*. All the other species recorded from the survey occurred on only one or two of the 16 sampled islands.

SPECIES ACCUMULATION ACROSS ISLANDS

While it is probable that individual islands still harbour additional taxa, it is less likely those taxa will add to the overall island species pool here. Species accumulation assessment using individual islands as samples shows that the Chao2 index and the second order Jacknife index are in close agreement with each other, having predicted 23.0 and 22.7 species, respectively, which is similar to our actual count of 22 species.

COMMUNITY ASSEMBLAGES

The SIMPROF routine in PRIMER identified four main groups of islands (shown in the nMDS ordination in Figure 2). The low level of stress (2D = 0.1) in the ordination shows that there was little distortion in the relative distance amongst the samples.

The geographic location of groups of islands identified by the PRIMER routine did not show many interpretable patterns (Figure 3). Group A included Sir Graham Moore and SW Osborn islands in the extreme north Kimberley, but also Adolphus Island in Cambridge Gulf near the NT border. Sir Graham Moore and Adolphus shared

TABLE 3 Characteristics (size, habitat preferences, refugia, breeding sites, chorus structure and call type) of frogs recorded from the 16 Kimberley islands included in the analysis. 'Size' is in mm and refers to maximum snout-urostyle length. Characteristics of some recently-discovered species (e.g. *C. fimbriata* and *U. micra*) are based on very limited observations compared to common species such as *L. caerulea* and *C. australis*. We have generally followed Tyler and Doughty (2009) and references therein which are based on mainland observations. (* highly dimorphic species with males only to 41 mm)

Species	Size	Habitat preferences	Refugia	Breeding sites	Chorus structure and call type
Hylidae					
Cyclorana australis	102	Terrestrial, loose soils	Burrower	Newly-formed ponds	Early wet season breeder; loud deep honking calls
Cyclorana longipes	55	Terrestrial, loose soils	Burrower	Ponds	Varies from explosive breeder to steady caller; loud rising call like mooing cattle
Litoria aurifera	22	Saxicoline, rockholes, rocky creeks	Rock crevices	Rockholes, rocky creeks	Loose choruses form along rocky creeks; high-pitched Morse Code-like call
Litoria bicolor	35	Arboreal, grasslands	Sedges	Swamps, flooded grasslands, slow-flowing creeks	Calls from sedges throughout the wet season; a ratchet-like sound
Litoria caerulea	110	Arboreal, trees and rocks	Tree hollows, rocks	Ponds	Calls from trees near water bodies throughout the wet season; raucous barking call
Litoria cavernicola	60	Arboreal, rocks and trees	Tree hollows, rocks	Rock pools	Calls from rocks or trees after rainfall; a repetitive squawk
Litoria coplandi	42	Saxicoline, rockholes, rocky creeks	Rock crevices	Rocky creeks, rockholes	Dispersed choruses form along rocky creeks; soft whirring call
Litoria meiriana	22	Saxicoline, rockholes, rocky creeks	Rock crevices	Rockholes, rocky creeks	Dispersed choruses form along rocky creeks; penetrating repetitive bleating call
Litoria nasuta	55	Terrestrial, grasslands	Sedges	Flooded grasslands	Large choruses form on the edges of ponds, streams and ditches; bursts of rapid high-pitched repeating call
Litoria rothii	50	Arboreal, often terrestrial	Hollows, under tree bark and in rock crevices	Swamps, shallow still seasonal wetlands	Dispersed choruses, calls throughout wet season; a far-reaching descending trill often from arboreal site
Litoria rubella	43	Arboreal, terrestrial (generalist)	Tree hollows, vegetation	Swamps, shallow still seasonal wetlands	Dispersed choruses; a loud seagull-like call
Litoria splendida	118	Arboreal, saxicoline	Tree hollows, rocks	Ponds near rocks	Rarely heard calling; a deep buzz-like call

Species	Size	Habitat preferences	Refugia	Breeding sites	Chorus structure and call type
Litoria staccato	39	Saxicoline, rockholes, rocky creeks	Rock crevices	Rockholes, rocky creeks	Dispersed choruses form along rocky creeks; a high-pitched repetitive call
Litoria watjulumensis	70*	Terrestrial, grasslands and rocky creeks	Rock crevices, sedges	Rocky creeks, flooded grasslands	Choruses form late in the evening; complex clucking and trilling calls
Myobatrachidae					
Crinia bilingua	29	Terrestrial, grasslands	Sedges	Flooded grasslands, slow-flowing creeks	Large choruses form in grasslands and creeks; a high-pitched rattle or clicking calls for long periods
Crinia fimbriata	17	Terrestrial, rock platforms	Unknown	Sandstone platforms	Small choruses in rock pools, call unknown
Uperoleia borealis	32	Terrestrial, creek lines	Rocks, sedges	Rocky creeks	Linear choruses form along creek lines; a loud squelch
Uperoleia crassa	34	Terrestrial, grasslands	Sedges	Flooded grasslands	Large choruses form in flooded grassy areas; call a loud rasp
Uperoleia lithomoda	32	Terrestrial, grasslands	Sedges	Flooded grasslands	Large choruses form in flooded grassy areas; call a loud click
Uperoleia micra	22	Terrestrial, rock platforms, rocky creeks	Rocks, sedges	Rock platforms, rocky creeks	Small choruses form in rock pools or along creeks; call a high-pitched rasp
Limnodynastidae					
Limnodynastes lignarius	61	Rocky creeks	Rock crevices	Rocky creeks	No choruses; a hollow tapping call from a sheltered position
Notaden weigeli	80	Sandstone platforms	Rock crevices, burrower	Ponds near rocks	No large choruses known, males call from rock platforms near water; a loud ‘whoop’
Platyplectrum ornatum	50	Terrestrial, generalist	Burrower	Flooded grasslands, swamps	Early wet season breeder, explosive choruses, carnivorous tadpoles; call a loud hollow ‘plonk’

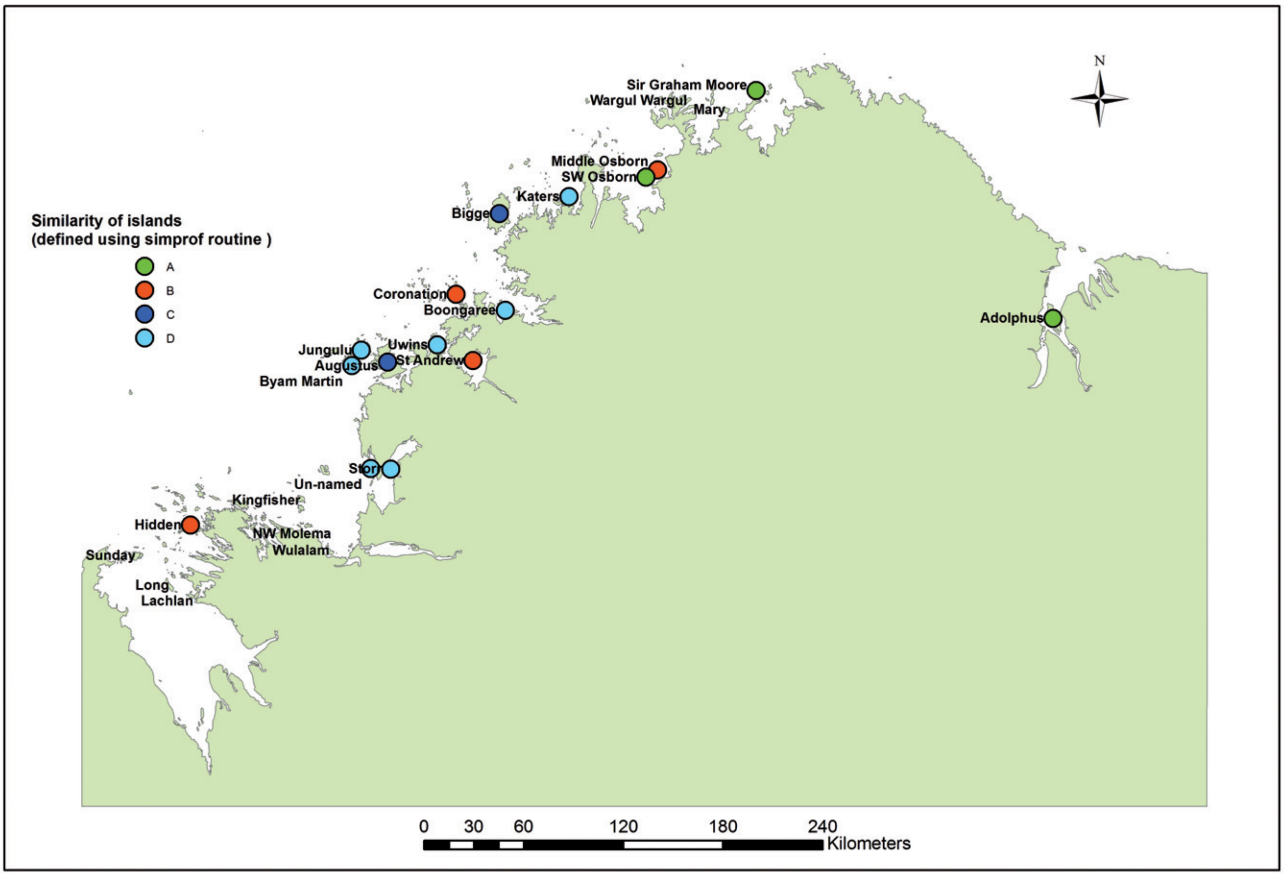

FIGURE 3 Map of the Kimberley showing the four groups of frog assemblages identified by the SIMPROF analysis. The 16 islands surveyed are shown, as well as eight islands that were not included in the analysis as no frogs were detected or they were not sampled in the wet season (i.e. Mary and Wargul Wargul).

many species not occurring elsewhere on surveyed islands (Table 2). The inclusion of SW Osborn Island in this group, however, appears due to the presence of *Uperoleia crassa* that also occurred on Sir Graham Moore Island. Group B islands were relatively species-poor; all (except Hidden Island) had the large hylid *L. caerulea*. Hidden Island only had the common *U. borealis*, whereas Middle Osborn was the only other island included in the analysis that had only a single species record (*L. caerulea*). Group C was comprised of Bigge and Augustus, by far the two largest islands and both with high species richness. They are in relative proximity to each other in the Bonaparte Archipelago (Figures 1 and 3) and share many species (Table 2). Group D consisted of the remaining seven islands, and were united by the three commonest species *L. lignarius*, *L. staccato* and *U. borealis*. Boongaree Island was somewhat similar to the two large Group C islands (Table 2), and was also diverse with nine species. However, the composition of the Boongaree Island frog fauna differed sufficiently from that of Bigge and Augustus that it was included with Group D (Table 2).

ENVIRONMENTAL CORRELATES OF ASSEMBLAGE STRUCTURE

While we attempted to examine the relationship between community structure and island environmental attributes, the highest Spearman rank correlation achieved was only 0.432, based on a combination of three variables: 'boulder' (a derived measure of the ruggedness of an island), 'maximum temperature of the warmest period of the year' and island area (log transformed). While the relevance of these variables in determining the frog assemblages is apparent, we were surprised that others such as rainfall showed almost no correlation. This lack of correlation to rainfall-related variables is likely to be a consequence of species responding to attributes at the scale of individual sites, which we did not measure, rather than the broader island attributes or environmental gradients across the island groups.

DISCUSSION

As a result of the survey, new records of frog species from nearly all the islands sampled were detected. Previous vertebrate surveys of the islands (e.g. Burbidge and McKenzie 1978; Start et al. 2007) have primarily targeted mammals by trapping and spotlighting in the dry season (see also Gibson and McKenzie 2012b). Not surprisingly, few frogs were known from the islands prior to this survey (Smith and Johnstone 1978; Maryan and Reinhold 2009). We found that wet season surveys were successful in locating numerous species of frogs as they were active with males calling on most nights. Some species, however, called rarely and did not form large choruses of breeding males. Examples are the large green tree/rock frog *L. splendida* and the large-bodied burrowing/rock frog *N. weigeli*. The detection of such species was reliant on observing individuals and consequently, they were more likely to go undetected than species that formed conspicuous choruses. Wet season surveys were difficult for logistical reasons, especially access. The islands are remote, and distant from settlements and ports. The wet season is also characterised by heavy rainfall and the risk of cyclones. Despite these difficulties, during the wet season surveys we were able to document a large number of species on islands from single night visits.

PATTERNS OF DIVERSITY

Based on the potential pool of frog species that occur on the mainland Kimberley adjacent to the islands, we found that many species were absent from the islands we surveyed (Table 4). In general, islands had depauperate frog faunas compared to the mainland, especially several frog groups that are diverse on the Kimberley mainland but not represented on islands (Tyler and Doughty 2009). Notable amongst these 'missing' frogs are five species of *Litoria* ground hylids: *L. axillaris*, *L inermis*, *L. nasuta*, *L. pallida* and *L. tornieri*. Only *L. nasuta* occurred on Boongaree Island which is only 100 m from the mainland, although separated by a deep channel, and *L. watjulumensis* occurred on three islands. Interestingly, both of these species have slightly expanded toe pads which assist in locomotion on rocks (Tyler and Doughty 2009). Of two Kimberley small-bodied sedge frogs, *Litoria bicolor* was only found on Sir Graham Moore Island while the tiny *L. microbelos* was not found on any island. Several burrowing frogs (e.g. *Notaden melanoscaphus*), wetland frogs (*Limnodynastes convexiusculus* and *Limnodynastes depressus*) and *Uperoleia* species were also not detected (see Table 4).

In contrast, there were three nearly ubiquitous species on the islands: *L. lignarius*, *L. staccato* and *U. borealis* (Tables 2, 3). These three species were also the only frogs detected on islands greater than 10 km from the coast (Byam Martin, Jungulu and Champagny; Table 2, Appendix 1). All three species breed in rocky creeks or streams on the mainland (Tyler and Doughty 2009; pers. obs.). Rocky creeks and rock pools are the habitats on islands most likely to have running or standing water during the wet season, and to have moisture during the dry season as well. It is therefore likely that these species are well suited for persisting on Kimberley islands.

When morphologically similar species pairs of Kimberley frogs were considered, there was a pattern discernible in some genera with the species preferring more rugged terrain occurring on islands over the less saxicoline species. For example, *L. staccato* was found to be more abundant on islands than *L. coplandi*; *L. watjulumensis* occurred on islands more often than other ground hylids; and *N. weigeli* was found on three islands, but all other species of *Notaden* were absent. This suggests that the species that favour the more rugged terrain on islands may possess physiological, morphological and behavioural adaptations, relative to their congeners, that enable them to persist in the drier conditions found on islands. For example, the *Litoria* species mentioned above, plus *L. aurifera/meiriana*, breed in rocky creeks during the wet season, but all these species are rarely found far from creek lines or rock pools with the exception of *L. staccato* and *L. watjulumensis* which are often seen distant from water (pers. obs.).

COMMUNITY ASSEMBLAGES

Island groups identified in the analysis were based on species co-occurrences of frogs among islands (Figures 2 and 3). We review the four groups below.

GROUP A: ADOLPHUS, SIR GRAHAM MOORE, SW OSBORN ISLANDS

This group of islands included the eastern-most islands sampled, with Adolphus in the Cambridge Gulf north of Wyndham and Sir Graham Moore north of Kalumburu near the Anjo Peninsula. Although widely separated by the north-east Kimberley coast (with only a few tiny islands close to the mainland), these two islands shared four species that were rare on the other islands: the medium to large-bodied burrowing species *C. australis*, *Cyclorana longipes* and *P. ornatum*, and the small-bodied tree frog *L. rubella*. In addition, the small sedge frog *L. bicolor* was only recorded on Sir Graham Moore (albeit with much larger body size than *L. bicolor* elsewhere in the Kimberley; PD, unpublished data). This island pair each supported a species of *Uperoleia* that prefers to breed in flooded grasslands: *U. lithomoda* on Adolphus and *U. crassa* on Sir Graham Moore. For each island, the

TABLE 4 Species of frogs not detected on Kimberley islands, but known from areas of the mainland adjacent to the surveyed islands (based on distribution maps in Tyler and Doughty [2009] and data in Doughty [2011]). Comments list possible morphological or behavioural features that may explain the absence of these species from Kimberley islands.

Species	Comments, including possible reasons for non-detection on islands
Hylidae	
Cyclorana cryptotis	Large-bodied burrowing species. Does not occur on mainland near islands, except near Adolphus Island.
Cyclorana vagitus	Large-bodied burrowing species. Does not occur on mainland near islands, except near Adolphus Island.
Litoria axillaris	Small non-burrowing ground frog, known from only two locations on the mainland. Candidate for islands of the Bonaparte Archipelago.
Litoria inermis	Small non-burrowing ground frog.
Litoria microbelos	Tiny non-burrowing sedge frog. Candidate for northern islands and Adolphus Island.
Litoria pallida	Small non-burrowing ground frog.
Litoria tornieri	Small non-burrowing ground frog.
Myobatrachidae	
Uperoleia aspera	Small burrowing ground frog. Candidate for Sunday Island.
Uperoleia marmorata	Taxonomic status uncertain, only known from type specimen with vague collection locality.
Uperoleia minima	Small burrowing ground frog. Breeds in flooded grasslands.
Uperoleia mjobergii	Small burrowing ground frog. Candidate for Sunday Island.
Uperoleia talpa	Small-medium burrowing ground frog. Candidate for Sunday and islands of the Buccaneer Archipelago.
Limnodynastidae	
Limnodynastes convexiusculus	Medium to large ground frog. Prefers permanent wetlands.
Limnodynastes depressus	Medium to large ground frog. Prefers permanent wetlands. Does not occur on mainland near islands, except possibly near Adolphus.
Notaden melanoscaphus	Medium to large burrowing frog. Does not occur on mainland near islands, except near Adolphus and Sir Graham Moore islands.

grassland species detected was the one occurring on the adjacent mainland.

Interestingly, SW Osborn was grouped with these eastern islands, based on the weight of *U. crassa* only occurring on SW Osborn and Sir Graham Moore. The other species on SW Osborn was *L. lignarius*, one of the three common island species. This example illustrates some of the tenuous links of island assemblages recovered when there are few species detected.

GROUP B: ST ANDREW, HIDDEN, CORONATION, MIDDLE OSBORN ISLANDS

The placement of Hidden Island in this group was somewhat surprising as it only possessed the common *U. borealis*. The other three islands were the only ones where *L. caerulea*, abundant on the mainland, was observed to occur. On Middle Osborn, *L. caerulea* was the only species recorded and the individuals encountered were found in a very rugged and steep creek. The other sampling site on Middle Osborn could not be surveyed during the wet season and so may possess additional species. Apart from *L. caerulea*, the only other species on Coronation was *U. borealis*, which was also present on St Andrew. The latter also had the relatively common island species, *L. lignarius*.

Interestingly, St Andrew had two species not common on other islands: *C. australis*, which elsewhere only occurred on the Group A islands, and *L. rothii*, also known from Boongaree and Storr islands. St Andrew is relatively steep and rocky, thus seemingly not ideal for the burrowing *C. australis*, and the island has only small patches of *Pandanus* that the arboreal *L. rothii* prefers. This island is located in St George Basin near the mouth of the Prince Regent River, a major watercourse emptying a vast area of the north-west Kimberley, so it is possible that *C. australis* and *L. rothii* may have rafted to St Andrew on debris washed downstream during the wet season.

GROUP C: AUGUSTUS AND BIGGE ISLANDS

These two islands are much larger than any other Kimberley island (both >17,000 ha) and as expected, had the highest species diversity. Bigge was the most diverse with 10 frog species recorded, and Augustus had eight species. Their faunas included the common species, *L. staccato* and *U. borealis*, but surprisingly *L. lignarius* was not recorded from Bigge despite the presence of extensive suitable habitat. Consequently, this species was probably missed by our sampling. Another possible species not detected was the large green tree frog *L. caerulea*, although *L. splendida*, an even larger-bodied tree frog, was recorded from both islands. The specialised tree and cave frog *L. cavernicola* is known from Bigge, but it is difficult to detect if cave systems are not located in the survey area. Given the extent of suitable habitat for this species on Augustus, it is likely that it is also present there. The large-bodied burrowing/rock-associated *N. weigeli* was detected on both islands, with the only other record coming from Katers Island (Group D, below). In addition to *L. staccato*, the other similar rock frog species *L. coplandi* also occurred on both islands, indicating that these islands provided sufficient niches for both these species. The small ground frog *C. bilingua* and the medium-sized ground/creek hylid *L. watjulumensis* were only detected on the islands in this group, as well as on Boongaree (Group D). All of these relatively large islands also had permanent water, which probably explains the persistence of these species on these islands. Additional species on Bigge included *L. meiriana* and *L. rubella* (the latter from a previous record [Smith and Johnstone 1978], but not recorded during our survey).

GROUP D: BOONGAREE, KATERS, STORR, UN-NAMED, BYAM MARTIN, JUNGULU AND UWINS ISLANDS

In this island group, Boongaree had nine species including the three common species (*Litoria staccato*, *L. lignarius* and *U. borealis*), plus *L. watjulumensis.* It also had the only records of the ground hylids, *L. nasuta* and *C. fimbriata* from any of the surveyed islands, and *L. rothii*, that was rare on the other islands (only occurring on St Andrew and Storr). Boongaree is a relatively large island (4614 ha) with both volcanic and sandstone geologies that in turn support diverse habitats, and is only 100 m from the mainland. As the channel separating Boongaree from the mainland is deep, connection was probably severed at the time of the sea level rises around 8000 years ago. Boongaree lies in Prince Fredrick Harbour which receives strong inflows of fresh water during the wet season from a number of rivers. This raises the possibility that rafting over the narrow channel has resulted in increased diversity on this island.

Katers Island was the most similar island to Boongaree in terms of its frog fauna. In common with Group C islands and Boongaree, Katers had a relatively high diversity with six frog species detected. The size of Katers, however, is much smaller (1713 ha) than the larger, more diverse islands, but it lies close (1.4 km) to the mainland. It had the three most common island species, plus three less-commonly encountered species associated with sandstone escarpments: *L. cavernicola*, *N. weigeli* and the small-bodied *Uperoleia micra* only known from Katers and Boongaree.

The remaining islands in Group D had fewer species. At least three of the common island species were present on all and were the only species on Uwins and Jungulu islands. Un-named and Storr also had *L. splendida*, and Storr had *L. rothii*. *Litoria staccato* and *U. borealis* were recorded on Byam Martin, but not *L. lignarius*, while Hidden only had *U. borealis*. The islands in this group were likely clustered together for their low diversity and presence of the three common species, with few other species present.

CONSERVATION IMPLICATIONS

Our survey generated many new records of frogs on a number of islands along the Kimberley coast. Nonetheless, further sampling will likely add to the inventory presented here. It is clear that the larger islands such as Augustus and Bigge have the greatest frog species richness and so are important for the conservation of insular Kimberley frogs. The moderately sized islands of Boongaree, Katers and Adolphus also have relatively high diversity and slightly different assemblages, reflecting the range of habitats available, general rainfall trends within the Kimberley region and presumably the available pool of species on the adjacent mainland when islands were isolated.

No threatened frogs are listed in the Kimberley region (Department of Sustainability, Environment, Water, Population and Communities 2012), however, the islands do retain populations of a number of frogs with restricted distributions and endemic Northern Kimberley taxa such as *C. fimbriata*, *L. aurifera*, *L. cavernicola*, *N. weigeli* and *U. micra.* Islands can beneficially isolate frog populations from disturbances on the mainland (e.g. pastoralism and changes to fire regimes) that impact other fauna (see Gibson and McKenzie 2012a, 2012b).

Many threatening processes have been identified as causing the decline and disappearance of frog taxa in Australia and world-wide including: habitat destruction, changes to hydrology, pollution, predation by introduced fish, climate change altering precipitation patterns, increased ultra-violet radiation and pathogens, especially the chytrid fungus, *Batrachochytrium dendrobatidis* (Tyler 1997; Daszak et al. 1999; McDonald and Alford 1999). Fortunately, many of these threats are absent on the Kimberley islands. Islands have been little changed by human activities in recent times with no modifications to their hydrology, or the establishment of land uses that require the use of pesticides. Koolan and Cockatoo islands have been mined extensively for iron ore and future mining activities are planned for the nearby Irvine Island, although none of these islands were sampled during our survey.

Future climate predictions for Australia (CSIRO and Bureau of Meteorology 2012) suggest that average temperatures will rise by 0.6 to 1.5°C by 2030. While annual rainfall may increase in northern Australia, it is likely (>66% probability) that fewer but more intense tropical cyclones will occur. While it would appear that such predictions offer frogs on Kimberley islands an ideal warmer and wetter environment in the future, rainfall unpredictability and the prospect of more frequent intense cyclones may result in the islands becoming more challenging environments for the breeding and survival of frogs.

Chytrid fungus has been linked to amphibian declines in Australia, Central America and the U.S.A. In Australia, its impact has been most pronounced in high altitude rainforest species (Berger et al. 1999). Chytrid has not yet been found to infect Kimberley frogs, but there has been little sampling of populations. While chytrid fungus has not been shown to be carried by Cane Toads (*Rhinella marina*) at the invasion front (Shine 2010), its mechanisms for invading areas need to be better understood to enable assessment of its risk to Kimberley frogs, including those occurring on islands.

Cane toads are advancing across the Kimberley at around 50 km/yr (Phillips et al. 2006; Urban et al. 2008) and are already on the Kimberley coast adjacent to Adolphus Island. At the current rate of spread, toads could be expected to be on the north Kimberley coast adjacent to other islands we sampled over the next 5–10 years. The ecological impact of introduced Cane Toads on native frogs has been an area of much conjecture, complicated by the difficulties in assessing change in frog populations. In a review of Cane Toad impacts on Australian fauna, Shine (2010) concluded that toads may affect native frogs in a range of negative ways: through competition for food or shelter in larval (tadpole) and adult stages; via lethal ingestion by native frogs of the toad's toxic eggs, tadpoles or sub-adults; or the transfer of parasites from toads to native frogs. The only potential positive effect identified was that reductions in *Varanus* lizard numbers due to toad poisoning would reduce predation on native frogs.

Cane toads colonised most of the islands in the Sir Edward Pellew group, which is adjacent to the mouth of McArthur River in the Gulf of Carpentaria, following extensive flooding in the wet season of 2001/02 (Rankmore 2005). Toads appear to have rafted on freshwater plumes and debris associated with the floods to these islands, including North Island, which is 25 km from the mainland. This suggests that Cane Toads are likely to raft or swim to many Kimberley islands, particularly some of the larger islands located near river mouths that we surveyed. The rocky nature of mesic environments on the islands is unlikely to favour extensive breeding by Cane Toads, and the hot dry seasons are likely to limit their population growth, and therefore reduce levels of competition with native taxa. While it is undesirable to have Cane Toads on Kimberley islands and efforts should be made to prevent their colonisation, it does appear unlikely that toads would have any major and long-term impact on insular frogs.

FUTURE WORK

Our island surveys have provided inventories of frogs for just 22 islands along the Kimberley coast. Further survey work on these islands and many more unsurveyed islands would be valuable to add to our knowledge of the biota of this region. Fieldwork in the area is logistically difficult, especially in the wet season when frogs are most easily detected. Any future surveys should aim to visit more sites on individual islands for more nights and target specific habitats for some of the species that are known to occur on the adjacent mainland. Systematic sampling of tadpoles and the use of pitfall or funnel traps may assist in the detection of some cryptic species of frogs when they are not calling. Automated recording devices provide a useful tool to detect frogs over long periods of the wet season and so avoid the problem of reduced frog activity (and hence detection probability) if there has not been rain immediately before or during a sampling period. Future work will also involve consultation with Traditional Owners.

ACKNOWLEDGEMENTS

The survey involved many people and we wish to thank our colleagues from the WA Department of Environment and Conservation (DEC), WA Museum, Kimberley Land Council, the participating Traditional Owners, Aboriginal Rangers, R. Teale and base camp volunteers. We thank the skippers and crews of *MV Kimberley Escape* and *MV Odyssey* and Tim Anders and other pilots from Heliwork and Broome Helicopters for transporting teams safely on and off islands. We are grateful to the DEC Kimberley regional manager Darryl Moncrieff and the staff in the Kununurra and Broome offices for their support during the project. DEC rangers at Mitchell River National Park, Lindsey Baker and John Hayward, provided valuable logistic support, as did the Truscott airbase staff during the first year. The project was possible through a research agreement with the Kimberley Land Council on behalf of the Balanggarra and Mayala native title claim groups and the Bardi-Jawi, Dambimangari and Uunguu native title holding groups. Funding was provided by the Natural Heritage Trust and DEC.

REFERENCES

Anstis, M. (2002). *Tadpoles of south-eastern Australia: a guide with keys*. Reed New Holland: Sydney.

Anstis, M., Tyler, M.J., Roberts, J.D., Price, L.C. and Doughty, P. (2010). A new species of *Litoria* (Anura: Hylidae) with a highly distinctive tadpole from the north-western Kimberley region of Western Australia. *Zootaxa* **2550**: 39–57.

Berger, L., Speare, R. and Hyatt, A. (1999). Chytrid fungi and amphibian declines: overview, implications and future directions (pp 23–33). *In*: Campbell, A. (ed), *Declines and disappearances of Australian frogs*. Environment Australia: Canberra.

Bowman, D.M.J.S., Brown, G.K., Braby, M.F., Brown, J.R ., Cook, L.G., Crisp, M.D., Ford, F., Haberle, S., Hughes, J., Isagi, Y., Joseph, L., McBride, J., Nelson, G. and Ladiges, P.Y. (2010). Biogeography of the Australian monsoon tropics. *Journal of Biogeography* **37**: 201–216.

Burbidge, A.A. and McKenzie, N.L. (1978). *The islands of the north-west Kimberley: Western Australia*. Wildlife Research Bulletin Western Australia No. 7. Department of Fisheries and Wildlife: Perth.

Clarke, K.R., Somerfield, P.J. and Chapman, M.G. (2006). On resemblance measures for ecological studies, including taxonomic dissimilarities and a zero-adjusted Bray-Curtis coefficient for denuded assemblages. *Journal of Experimental Marine Biology and Ecology* **330**: 55–80.

Clarke, K.R. and Gorley, R.N. (2006). *Primer v6 User Manual/Tutorial*. Primer-E Ltd: Plymouth, U.K.

CSIRO and Bureau of Meteorology (2012). State of the Climate 2012. http://www.csiro.au/Portals/Media/State-of-the-Climate-2012.aspx

Dasczak, P., Berger, L., Cunningham, A.A., Hyatt, A.D., Green, D.E. and Speare, R. (1999). Emerging infectious diseases and amphibian populations declines. *Emerging Infectious Diseases* **5**: 735–748.

De Deckker, P. and Yokoyama, Y. (2009). Micropalaeontological evidence for Late Quaternary sea-level changes in Bonaparte Gulf, Australia. *Global and Planetary Change* **66**: 85–92.

Department of Sustainability, Environment, Water, Population and Communities (2012). EPBC Act List of Threatened Fauna 2012. http://www.environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl?wanted=fauna

Doughty, P. (2011). An emerging frog diversity hotspot in the northwest Kimberley of Western Australia: another new frog species from the high rainfall zone. *Records of the Western Australian Museum* **26**: 209–216.

Doughty, P., Anstis M. and Price, L.C. (2009). A new species of *Crinia* from the high rainfall zone of the northwest Kimberley, Western Australia. *Records of the Western Australian Museum* **25**: 127–144.

Doughty, P. and Anstis, M. (2007). A new species of rock-dwelling hylid frog (Anura:Hylidae) from the eastern Kimberley region of Western Australia. *Records of the Western Australian Museum* **23**: 241–257.

Gibson, L.A. and McKenzie, N.L. (2012a). Identification of biodiversity assets on selected Kimberley islands: background and implementation. *Records of the Western Australian Museum Supplement* **81**: 1–14.

Gibson, L.A. and McKenzie, N.L. (2012b). Occurrence of non-volant mammals on islands along the Kimberley coast of Western Australia. *Records of the Western Australian Museum*, Supplement **81**: 15–39.

Houlder, D., Hutchinson, M., Nix, H. and Mcmahon, J. (2000). *ANUCLIM user guide*, version 5.1. Centre for Resource and Environmental Studies, Australian National University: Canberra.

How, R.A. and Cowan, M.A. (2006). Collections in space and time: geographical patterning of native frogs, mammals and reptiles through a continental gradient. *Pacific Conservation Biology* **12**: 111–133.

How, R., Schmitt, L., Teale, R. and Cowan, M. (2006). Appraising biodiversity on Bonaparte Islands, Kimberley, Western Australia. *Western Australian Naturalist* **92**: 92–100.

Lever, C. (2003). *Naturalized reptiles and amphibians of the world*. Oxford Univesity Press: New York.

Losos, J.B. and Ricklefs, R.E. (eds) (2010). *The theory of island biogeography, revisited.* Princeton University Press: Princeton.

McArthur, R. and Wilson, E.O. (1967). *The theory of island* *biogeography*. Princeton University Press: Princeton.

McDonald, K. and Alford, R. (1999). A review of declining frogs in Northern Queensland (pp 14–22). *In*: Campbell, A. (ed). *Declines and disappearances of Australian frogs*. Environment Australia: Canberra.

Magurran, A.E. (2004). *Measuring biological diversity*. Blackwell Publishing: Malden, U.S.A.

Maryan, B. and Reinhold, L. (2009). Additions to the terrestrial herpetofauna of Koolan and Dirk Hartog Islands. *Western Australian Naturalist* **27**: 18–24.

Nix, H.A. and Kalma, J.D. (1972). Climate as a dominant control in the biogeography of Northern Australia and New Guinea. *In*: Walker, D. (ed), *Bridge and barrier: the natural and cultural history of Torres Strait*. Research School of Pacific Studies Publication B6/3. Australian National University: Canberra.

Phillips, B.L., Brown, G.L., Webb, J.K. and Shine, R. (2006). Invasion and the evolution of speed in toads. *Nature* **439**: 803.

Powney, G.D., Grenyer, R., Orme, C.D.L., Owens, I.P.F. and Meiri, S. (2010). Hot, dry and different: Australian lizard richness is unlike that of mammals, amphibians and birds. *Global Ecology and Biogeography* **19**: 386–396.

Rankmore, B. (2005). Introduced animals on Northern Territory islands: improving Australia's ability to protect its island habitats from feral animals. Report by the Department of Natural Resources, Environment and the Arts, NT to the Department of Environment and Heritage: Canberra.

Shine, R. (2010). The ecological impact of invasive Cane Toads (*Bufo marinus*) in Australia. *Quarterly Review of Biology* **85**: 253–291.

Slatyer, C., Rosauer, D. and Lemckert, F. (2007). An assessment of endemism and species richness patterns in the Australian Anura. *Journal of Biogeography* **34**: 583–596.

Smith, L.A. and Johnstone, R.E. (1978). Part V Amphibians and Reptiles (pp 42–45). *In*: Burbidge, A.A. and McKenzie, N.L. (eds), *The islands of the north-west Kimberley: Western Australia*, No. **7**. Department of Fisheries and Wildlife: Perth.

Start, A.N., Burbidge, A.A., McKenzie, N.L. and Palmer, C. (2007). The status of mammals in the north Kimberley, Western Australia. *Australian Mammalogy* **29**: 1–16.

Tyler, M.J. (1997). *The action plan for Australian frogs*. Wildlife Australia: Canberra.

Tyler, M.J. and Doughty, P. (2009). *Field guide to frogs of Western Australia*, fourth edition. Western Australian Museum: Perth.

Urban, M.C., Phillips, B.L., Skelly, D.K. and Shine, R. (2008). A toad less travelled: the heterogeneous invasion dynamics of Cane Toads in Australia. *American Naturalist* **171**: 134–148.

MANUSCRIPT RECEIVED AUGUST 2012; ACCEPTED NOVEMBER 2012.

APPENDIX 1 List of species from Kimberley islands not sampled during the survey and not included in the analysis (cf. Table 2, Figure 3).

Island	Species
Champagny	*Limnodynastes lignarius, Uperoleia borealis*
East Montalivet	*Uperoleia* sp. (based on squelching call)
Irvine	*Litoria splendida, Limnodynastes lignarius*
Koolan	*Litoria coplandi, Litoria rubella, Limnodynastes lignarius*
Mary	*Uperoleia* sp., *Platyplectrum ornatum*
Wargul Wargul	*Litoria caerulea*