



HAL
open science

A conservation paradox: endangered and iconic flightless kagu (*Rhynochetos jubatus*) apparently escape feral cat predation

Pauline Palmas, Herve Jourdan, L. Debar, Edouard Bourguet, Frédéric Rigault, E. Bonnaud, Eric Vidal

► To cite this version:

Pauline Palmas, Herve Jourdan, L. Debar, Edouard Bourguet, Frédéric Rigault, et al.. A conservation paradox: endangered and iconic flightless kagu (*Rhynochetos jubatus*) apparently escape feral cat predation. *New Zealand Journal of Ecology*, 2020, 44 (1), pp.3394. 10.20417/nzjecol.44.1 . hal-02545324

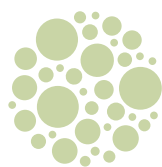
HAL Id: hal-02545324

<https://hal.science/hal-02545324>

Submitted on 8 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



A conservation paradox: endangered and iconic flightless kagu (*Rhynochetos jubatus*) apparently escape feral cat predation

Pauline Palmas^{1,2*} , Hervé Jourdan¹ , Léo Debar¹, Edouard Bourguet¹, Frédéric Rigault¹, Elsa Bonnaud²  and Eric Vidal^{1,3} 

¹ Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale (IMBE), Aix Marseille Université, CNRS, IRD, Avignon Université, Centre IRD de Nouméa, BPA5, 98848 Nouméa cedex, Nouvelle-Calédonie

² Ecologie Systématique Evolution, Université Paris-Sud, CNRS, AgroParisTech, Université Paris-Saclay, 91 400 Orsay, France

³ UMR ENTROPIE (IRD-Université de la Réunion-CNRS), Laboratoire d'Excellence Labex-CORAIL, Institut de Recherche pour le Développement, BP A5, 98848 Nouméa Cedex, Nouvelle Calédonie

* Author for correspondence (Email: pauline.palmas@ird.fr)

Published online: 7 February 2020

Abstract: The kagu (*Rhynochetos jubatus*) is an iconic endemic flightless bird from New Caledonia, red-listed as endangered according to the International Union for Conservation of Nature (IUCN) criteria. Feral cats are among the most successful and damaging invaders for island biodiversity. They have been directly responsible for the extinction of numerous birds worldwide, especially small- and medium-sized flightless species. Our study evaluates the feral cat threat to the kagu by analysing 772 cat scats from the two main sites housing major remaining populations (eight quarterly sampling sessions conducted per site over 2 years). Surprisingly, we detected no predation evidence against this endangered species (including chicks) although it falls within the cats' prey size range and exhibits life-history traits typical of island endangered naïve birds. We recommend a multi-species approach to invasive mammal management to mitigate direct and indirect pressures against remaining kagu populations.

Keywords: bird, conservation 'loser', *Felis catus*, invasive predator, island conservation, island ecosystems, threatened species, New Caledonia

Introduction

Domesticated thousands of years ago (Driscoll et al. 2007) and subsequently introduced by humans to islands worldwide, the domestic cat *Felis catus* has generally reached sustainable and even flourishing feral populations (Nogales et al. 2013). Feral cats are known to prey intensively upon native fauna, leading to numerous island species extinctions, extirpations and endangerment (e.g. Medina et al. 2011; Doherty et al. 2016). Feral cats feed on a wide range of prey, from large birds and medium-sized mammals exceeding 1–2 kg to small invertebrates (e.g. Bonnaud et al. 2011; Doherty et al. 2015). Cats are involved in the recent extinction of 63 insular vertebrate species (40 bird, 21 mammal, and 2 reptile species; 26% of all recent extinctions) (Doherty et al. 2016).

The dramatic loss of native island species has been mainly attributed to island prey naïveté (Carthey & Banks 2014). Endemic island flightless and ground-nesting birds are extremely vulnerable to introduced predators, especially feral cats (Roots 2006; Steadman 2006; Woinarski et al. 2017). Among the 40 worldwide bird species recently extinct (since AD 1500) partly or totally due to cat predation, at least 12 were flightless (Doherty et al. 2016); see Table S1 in Supplementary Material.

Cats were introduced to New Caledonia around 1860 by European settlers and are now present in a wide range of habitats, even in the most remote areas (Beauvais et al. 2006; Palmas et al. 2017). Throughout the New Caledonian archipelago, feral cats prey upon at least 44 native vertebrate species ranging from small insects to medium-sized birds and mammals (Palmas et al. 2017). Surprisingly, no remains of a flightless New Caledonian endemic bird, the kagu (*Rhynochetos jubatus*), were found among all the 5356 cat scats collected from the 14 study sites of a previous larger study (Palmas et al. 2017). This intriguing result motivated us to focus on cat scat sampling and analysing in the two major bastions for this bird species.

The kagu is an iconic endangered flightless ground-nesting forest bird endemic to New Caledonia (South Pacific) (see Figure S1 in Supplementary Material). Weighing c. 900 g, it combines all the vulnerability traits typical of island conservation 'losers': flightlessness, K-selected traits, and absence of shared evolutionary history with mammalian predators (Hunt 1997; Roots 2006; Steadman 2006). Today, kagu populations are mainly found in inland forested mountainous regions of the New Caledonia main island (Grande Terre) and appear fragmented among patches of rainforest

remnant habitat (Hunt 1997; BirdLife International 2016). During the last century, a general decline was observed for this species, mainly due to habitat loss, forest fragmentation, and potentially direct and indirect impacts of invasive species like dogs, rats, pigs and deer (Warner 1948; Hunt et al. 1996). The kagu has been IUCN red-listed as endangered. In 2016, whole-island monitoring reported c. 2000 wild kagu individuals (BirdLife International 2016), with 75.3% of the recorded individuals distributed in two major nature reserves (BirdLife International 2016), the focused sites of our study. Until the arrival of the first human settlers, 3200 years ago, and without the presence of native mammalian predators, the kagu was among the top native predators in natural forests, and thus, may not have developed anti-predator behaviour. All potential mammalian predators against the kagu were introduced to New Caledonia by humans, either Austronesian settlers 3200 years ago (Polynesian rat, *Rattus exulans*) or European colonisers during the first half of the 19th century (dogs, cats, black rats *Rattus rattus*, brown rats *Rattus norvegicus*, pigs; Beauvais et al. 2006). Feral cats are now widespread throughout the kagu distribution range and considered a major threat to this species (BirdLife International 2016), although the literature shows no clear evidence of cat predation (Hunt 1997; Rouys & Theuerkauf 2003; Gula et al. 2010).

Here, we used scat sampling and analysis to assess feral cat predation on the two main remnant populations of kagu, seeking to list the feral cat among the threats endangering this iconic endemic bird. We also studied feral cat diet according to kagu breeding cycle to detect any cat predation patterns that can differently affect kagu survival and productivity. To complete this trophic approach, we then examined, across all worldwide island bird and mammal species known to be preyed upon by feral cats, their morphological traits (i.e. weight and flight ability) to better understand the kagu's catchability.

Methods

Study sites

We conducted this study in the two New Caledonian nature reserves housing the two major remaining kagu populations

(BirdLife International 2016; Fig. 1). The Parc des Grandes Fougères (PGF) covers 45.45 km² of mainly rain forest vegetation on metamorphic soil. This forest has a high canopy (20–30 m) with a dense understorey, dominated by *Arecaceae*, *Sapindaceae*, *Meliaceae* and *Monimiaceae* (Ibanez et al. 2014). The floral endemism rate reaches 83% (Morat et al. 2012). The mean annual rainfall is between 1500 and 2000 mm (Meteo France 2007). This habitat covers 1800 km² of New Caledonia. The Parc Provincial de la Rivière Bleue (PPRB) covers 220.68 km² of mosaic habitat composed of rain forest vegetation and maquis shrubland on ultramafic soil (Isnard et al. 2016). The forest canopy reaches from 20 to 30 m. Mean annual rainfall is between 2500 and 3500 mm (Meteo France 2007). The maquis has heathy or scrubby vegetation with a low woody stratum (50 cm to 7 m). The maquis mosaic and rain forest flora endemism rates are respectively 96.9% and 96.4% (Isnard et al. 2016). This mosaic habitat is dominated by *Arecaceae*, *Sapindaceae*, *Meliaceae* and *Monimiaceae* (Ibanez et al. 2014) and covers 5600–5700 km² of New Caledonia.

Cat diet study according to kagu breeding cycle

Scat sampling at both sites took place in areas where kagu presence had been confirmed and mapped (Meriot et al. 2009; Boissenin 2012) and kagu were regularly observed during scat sampling.

There are two main periods that affect the kagu's degree of vulnerability to predators: the breeding period (June–December), and non-breeding period (January–May) (Létocart & Salas 1997). The breeding period corresponds to the highest vulnerability for kagu and includes the main laying period and juvenile rearing duration. We studied the feral cat diet by analysing scats collected along paths used by cats (Turner & Bateson 2014; Bonnaud et al. 2015) over 2 consecutive years, with samples collected every 3 months to cover the overall kagu breeding cycle, considering that scats reflected the two previous months of cat predation at most (Bonnaud et al. 2007). For each field session the cumulative sampling length effort cover 30.2 km for PPRB and 12.1 km for PGF. Cat scats were georeferenced, stored in individual Ziploc bags, and frozen until analysis. We analysed 335 scats for PGF and 437 scats for PPRB, representing a robust and significant sampling effort

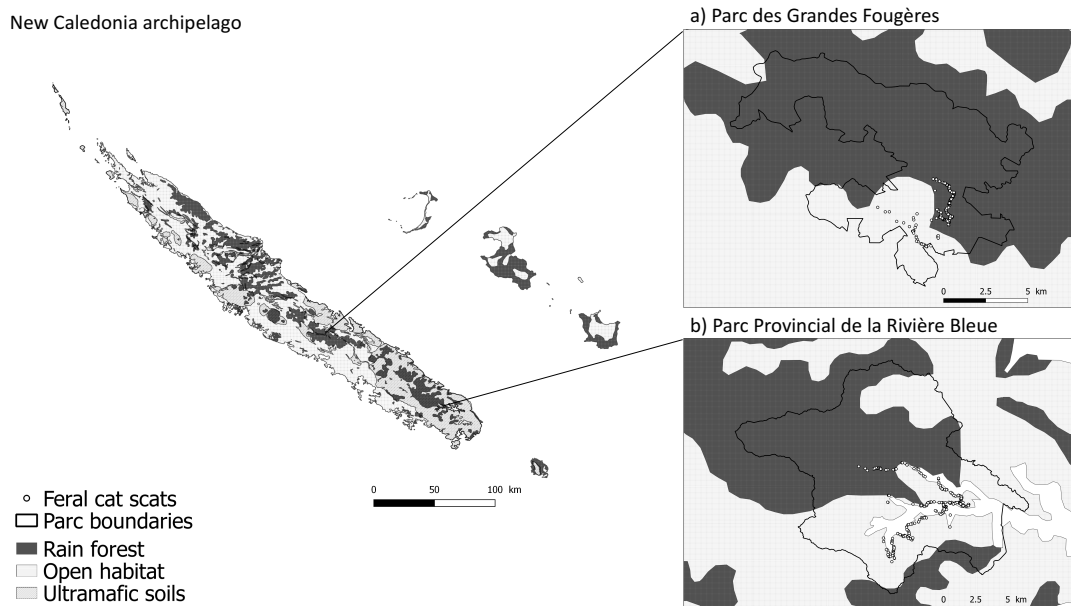


Figure 1. Location of the two New Caledonian nature reserves housing the main kagu populations; a) The Parc des Grandes Fougères (PGF); b) The Parc Provincial de la Rivière Bleue (PPRB). Circles indicate the location of collected and analysed feral cat scats.

($n > 100$) to track even rare prey remains (Bonnaud et al. 2011). Scats were dissected by washing over a 0.5 mm mesh size sieve and separating items like hair, feathers, bone fragments, claws, teeth, beaks, jaws, skink scales and arthropod chitin fragments. We compared each item to reference materials for assignment to one of the six main prey categories: introduced rodents, bats, birds, squamates, invertebrates and fish. Kagu remains available in our reference collection included beaks, claws, different types of feathers for adults and down for chicks.

Data analyses

For each type of cat prey, we calculated the frequency of occurrence (FO) per scat (Bonnaud et al. 2015). We used Levins' standardized formula for trophic niche breadth (Levins' SNB; Krebs 1999):

$$SNB = (B-1)/(n-1) \tag{1}$$

where $B = 1/\sum p_i^2$ with p_i the fraction of prey item i in the diet ($\sum p_i = 1.0$) and n the number of prey categories in the predator's diet. SNB ranges from 0 to 1, where a value close to 0 represents a narrow niche and one close to 1, a broad niche.

Statistical analyses

We conducted all statistical analyses with R 3.0.3 software (R core Team 2014) using 'pROC' (Fawcett 2006). We ran (1) Chi-square tests for homogeneity to test site effect on overall cat diet composition by comparing the FO of six prey categories; and (2) generalised linear models (GLM) to test site effect of occurrence of each prey in cat diet [in R: glm (response ~ site), family = binomial (link= "cloglog")]. We used area under the ROC-curve plot (AUC) to assess the accuracy of our model predictions (Fielding & Bell 1997). AUC values commonly range from 0.5 to 1.0 prediction, corresponding respectively to a random and perfect prediction.

Feral cats' prey sizes on islands

We compiled across all island bird and mammal species known to be preyed upon by feral cats according their morphological traits (i.e. median adult weight and flight ability). We produced

body-size frequency distribution by considering prey species with adult median body weight over 400 g (prey species and median weight from Bonnaud et al. 2011; Doherty et al. 2015; Avibase 2017; Birdlife International 2017; Myers et al. 2017). We considered only medium sized birds and mammals over 400 g in order to range the kagu within the cats' medium prey size range.

Results

Feral cat diet according to study site

Surprisingly, no remains of either adult or young kagu were found among the 772 feral cat scats collected within these two bastions of this species.

Overall cat diet composition differed between the two sites ($p < 0.001$) (Fig. 2). Cats had a wider standardised Levins' niche breadth in PPRB (Levins' SNB = 0.52) than in PGF (Levins' SNB = 0.30).

The GLM describing prey occurrences in cat diet for each site correctly predicted presence and absence of main prey groups (AUC ranging from 0.57 for birds to 0.78 for fish) (Fig. 2; Table 1). All studied prey groups showed significant differences: higher FO of rodents and squamates for PGF and higher FO of bats (mainly flying foxes), birds, invertebrates and fish for PPRB (Fig. 2; Table 1).

For PGF and PPRB, passerines were the predominant bird prey (in 14.3% and 14.8% of the scats containing bird remains respectively; Table 1), followed by seabirds for PGF (in 9.5% of scats containing bird remains). For PPRB, no seabird remains were found in cat scats.

Feral cat diet according to kagu breeding cycle

Cats had the widest standardised Levins' niche breadth in the kagu breeding period in PPRB (Levins' SNB = 0.62), and in the non-breeding period of the second sampling year in PGF (Levins' SNB = 0.36) (Fig. 3).

In PPRB, FO of rodents and squamates are much lower

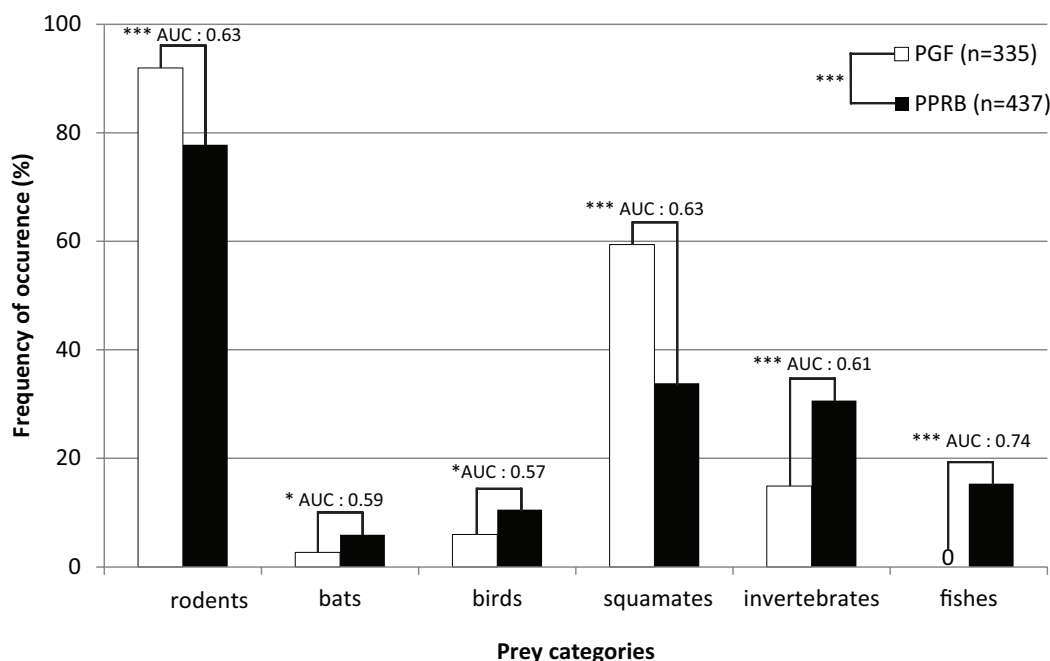


Figure 2. Frequency of occurrence (FO) of feral cat prey categories in the two study sites (n = 772); * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$; the area under the ROC-curve plot (AUC) ranging from 0.5 to 1.0 indicates the accuracy of model predictions.

during the kagu breeding period (respectively 69.6% for breeding period vs 83.7% non-breeding period for rodents, and 30.4% vs 48.9% for squamates), while FOs of birds (14.3% vs 3.7%), invertebrates (36.2% vs 30.3%), fish (21.2% vs 10.2%) and bats (6.7% vs 2.9%) are higher.

In PGF, FOs of rodents, birds and bats are similar between periods (respectively 91.0% vs 92.6% for rodents, 7.0% vs 5.2% for birds and 2.7 vs 2.3% for bats), while FO squamates and invertebrates (respectively 52.0% vs 69.7% and 5.6% vs 30.2%) are the highest during the kagu non-breeding period.

Kagu vulnerability: body weight of known bird and mammal preyed upon by feral cats

On worldwide islands and considering only birds over 400 g, island birds preyed upon by feral cats include at least 46 species, of which 14 are flightless, belonging to Sphenisciformes (10), Gruiformes (2), Apterygiformes (1), Casuariiformes (1) and weighing from 850 to 4000 g (Fig. 4). For island mammals, feral cats are known to prey upon at least 33 species over 400 g (Bonnaud et al. 2011; Doherty et al. 2015; Fig. 4).

Table 1. Results of (a) Chi-square tests for homogeneity to test site effect on overall cat diet composition by comparing the FO of the six prey categories (b) GLM to test site effect on occurrence of each prey in cat diet including AUC values for assessing the accuracy of our model predictions.

	Chi-squared	df	p-value
(a)	112.1	5	$< 2.2 \times 10^{-16}$

	Deviance explained	Pr(> Chi)	AUC
(b)			
Rodents	0.044	0.000	0.629
Bats	0.017	0.026	0.593
Birds	0.012	0.023	0.572
Squamates	0.047	1.29×10^{-12}	0.627
Invertebrates	0.032	2.21×10^{-07}	0.607
Fish	0.178	$< 2.2 \times 10^{-16}$	0.738

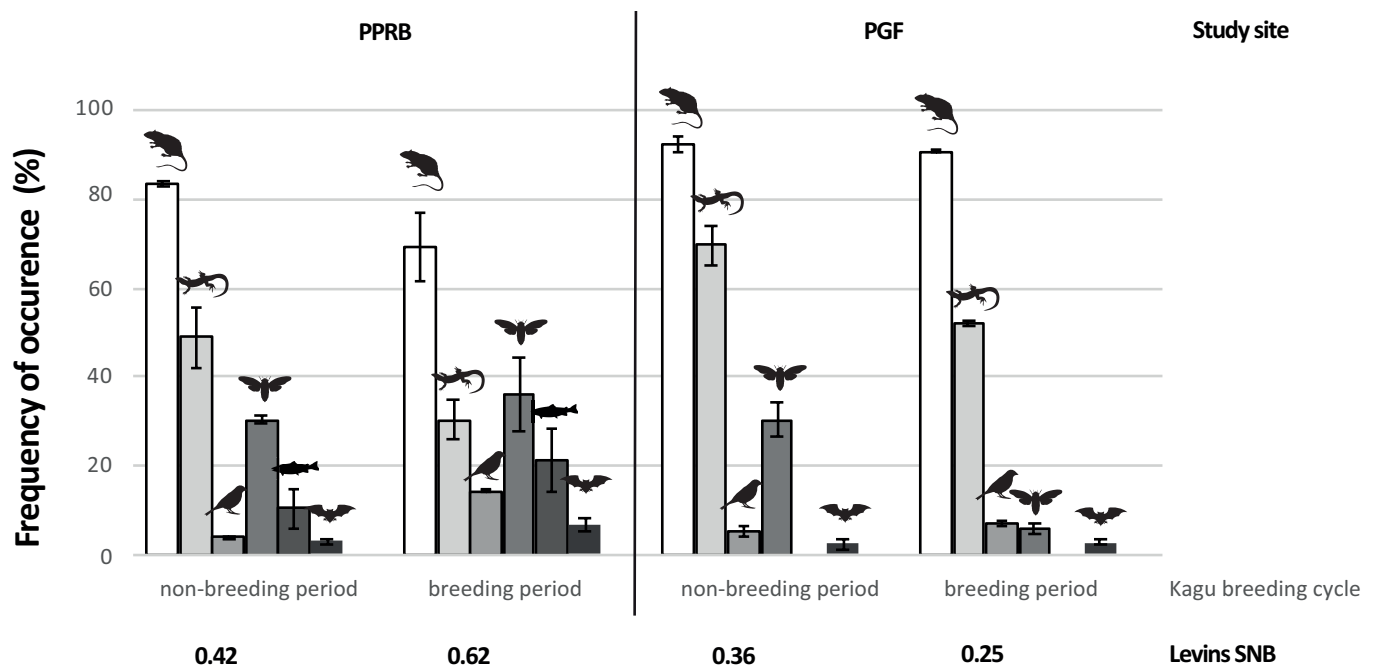


Figure 3. Cat diet and Levins SNB index for PPRB and PGF according to kagu breeding cycle; mean FOs of rodents, squamates, birds, invertebrates, fish and bats for the 2 consecutive sampling years.

Discussion

Pattern of feral cat diet according to study sites and kagu breeding cycle

Counter-intuitively, no kagu remains were found in the 772 feral cat scats analysed, despite the relatively abundant kagu populations recorded in both study sites (around 1000 and 500 individuals respectively for PGF and PPRB) (Meriot et al. 2009; Boissenin 2012) and the high diurnal activity observed for both kagu and cats (Palmas et al. unpubl. data). The apparent absence of predation by feral cats on kagu, even during their breeding period, is concordant with previous video-monitoring

of nests that did not record any feral cat visits (Rouys 2008).

From our diet results, feral cats exhibited a broader trophic niche in PPRB than in PGF, preying upon a wider range of species, all with higher FOs, except for introduced rodents and squamates. FOs of flying fox remains were higher in PPRB than in PGF despite the fact that no flying fox colonies are known in these parks (Le Goff & Brescia 2011). Predation on stranded fish (*Tilapia* sp.) in PPRB occurred over a short period corresponding to a massive seasonal drop in water levels of surrounding lakes. Such high FO (15.3%) for this prey group is striking and rarely mentioned in other cat diet studies. Cat predation on invertebrates (mostly insects) is frequent and comparable to the FO found previously on islands for PPRB

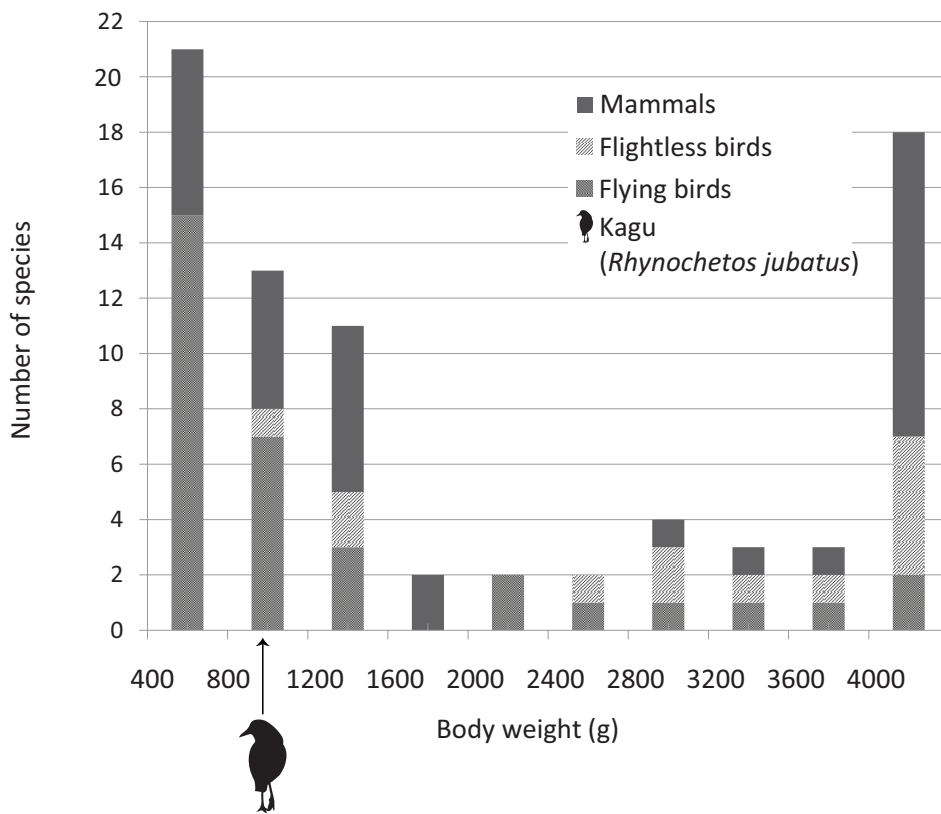


Figure 4. Body-size frequency distribution of medium- to large-sized bird and mammal species known to be consumed by feral cats on islands (weight ≥ 400 g) (preyed upon species and median weight from Avibase 2017; Birdlife International 2017; Bonnaud et al. 2011; Doherty et al. 2015; Myers et al. 2017). The arrow indicates the position of kagu according to median adult weight.

(mean of 32.57% (SD 4.9) in Bonnaud et al. 2011; mean of 36.15% (SD 2.78) for Australia in Doherty et al. 2015; FO: 30.7% in PPRB) despite the poor nutritive value of this small, unpalatable prey (Turner & Bateson 2014). These diet patterns, particularly in PPRB, suggest that feral cats look for additional food resources apart from rodents. This finding is consistent with the hypothesis of a lower productivity of ultramafic soils present in PPRB, which could imply a lower productivity and a subsequent lower prey availability than PGF (Guilbert 1997; Theuerkauf et al. 2017), and thus could lead to a higher foraging effort for cats in PPRB.

In PPRB feral cats showed a broader niche in kagu breeding period. Cats preyed upon a wider range of prey with higher FOs for birds, invertebrates and bats according to a lesser FO of rodents and squamates. The decrease of rodents in feral cat diet could be correlated to a decline in rodent abundance that could occur at this period in this type of habitat (Rouys 2008). Feral cats preyed upon more birds, invertebrates and bats during the kagu breeding period, indeed this period corresponds to the breeding period for terrestrial birds and flying foxes (Létocart & Salas 1997; Rouys 2008; Barré et al. 2013; Brescia; Boissenin & Brescia, unpubl. reports, see <http://www.iac.nc/ressources-publications/catalogue-en-ligne-gaiac>) leading to a higher abundance and vulnerability of these prey. Rather, the increase of invertebrates on feral cat diet during this period appears when invertebrate populations are at the lowest densities (Guilbert 1997). These diet patterns showed that feral cats look for alternative resources to rodents during this period (birds, invertebrates and bats), which possibly involved higher foraging effort whereas kagu are abundant and most vulnerable to predation.

In PGF feral cats showed a faintly broader niche in kagu non-breeding period, despite a constant predation on rodents. Feral cats preyed upon a slightly wider range of prey in the kagu non-breeding period with higher FOs for squamates

and invertebrates. These patterns showed the opportunistic predatory behaviour of feral cats, that prey more upon these two groups when they are more abundant between January and June (Cohic 1950; Guilbert et al. 1994; Guilbert 1997; Jourdan pers. comm.).

Kagu traits: vulnerability and management implications

On worldwide islands, cats prey upon a large range of vertebrate species weighing from few grams to several kilograms (e.g. Bonnaud et al. 2011). Considering only birds and mammals over 400 g, known prey include at least 79 different species (46 birds and 33 mammals) (Bonnaud et al. 2011; Doherty et al. 2015; Fig. 4). Cat consumption of prey over 4000 g could be related to scavenging (Forsyth et al. 2014), as mean feral cat weight is from 2400 to 4000 g (Burbidge & McKenzie 1989; Moseby & Read 2006; Goltz et al. 2008). Cats prey upon a total of 14 flightless bird species weighing from 850 to 4000 g. (Fig. 4).

Consequently, the kagu (adults around 900 g) falls within the feral cat prey range even though the highest likelihood for a bird to be killed by cats is to show intermediate body mass (c. 60–300 g; Woinarski et al. 2017). In addition, the kagu's flightlessness, ground foraging and ground nesting behaviours strongly increase vulnerability to predation, for instance by wild dogs (e.g. Hunt et al. 1996; Woinarski et al. 2017). Kagu were also regularly seen at short distances during scat sampling, that demonstrated their naïve and confident behaviour. However, adult kagu may have developed effective defensive behaviour against aggressive approaches, which further investigations could confirm. One defensive strategy is 'opening their wings to display their black and white banded primary feathers' (Hunt et al. 1996), thereby conveying their large size as a deterrent to cats. In addition, authors observed adult kagu in the nest, or chicks flapping their wings on the ground, that could be distractive or a deterrent for cats. Another strategy

is using cooperative breeding behaviour, which may help to reduce predation on chicks (Theuerkauf et al. 2009). Indeed, breeding kagu and their helpers could use the behaviours mentioned above to defend chicks from cat predation. Kagu have been described attacking dogs as they captured other kagu (Hunt 1997). This defence behaviour seems inefficient against dog predation (e.g. Sarasin 1913) but could probably be efficient against cat predation, given the smaller size of feral cats than wild dogs, and given the solitary habits of cats contrasting with the dog pack behaviour for hunting. This defence behaviour seems also particularly efficient against rodent predation, without any predation events on eggs or chicks as revealed during a dedicated study (Rouys 2008). One additional explanation to this striking absence of cat predation is that feral cats in New Caledonia exhibit a rather small size (mean weight for trapped males 2.23 ± 0.83 kg ($n = 17$) and for females 1.64 ± 0.55 kg ($n = 37$); unpubl. data) that could reduce their predation capacity on medium-sized prey like the kagu.

Some studies reported interesting results about feral cat impacts on large ground dwelling birds. In New Zealand, kiwi (*Apteryx* spp.) are vulnerable to feral cat predation during chick and juvenile stages. Indeed, McLennan et al. (1996) revealed that feral cats were largely responsible for the death of young kiwi, whereas ferrets and dogs are the main predators for adults. On the contrary the malleefowl (*Leipoa ocellata*) in Australia apparently escape feral cat predation (Dickman 1996) while red foxes (a larger predator) have been confirmed as the primary cause of failure of reintroduction for this bird species (high predation rate in fragmented habitats).

While morphological diet studies have greatly contributed to our understanding of invasive species' diets, this method may be constrained by resolution detection and identification, particularly for rare prey (Zarzoso-Lacoste et al. 2016). Using DNA-based methods (e.g. metabarcoding) would help to confirm the absence or extreme rarity of kagu in cat diet.

Even though predation by cats has by far the strongest deleterious effect on native island bird wildlife (e.g. Medina et al. 2011; Bonnaud et al. 2015), to date this flightless, endangered and endemic bird seems to have escaped this direct threat. However, cats could potentially affect kagu survival and fitness by killing and not consuming them or by frequently attempting to capture individuals that actually escape but are injured (Lloyd et al. 2013; McRuer et al. 2017). Furthermore, cats were found to prey extensively upon skinks and terrestrial arthropods, two of the main prey groups for the kagu (Létocart & Salas 1997). Cats may thus be an indirect threat considering competition for food (e.g. Medina et al. 2014), especially when resources are limited (Guilbert et al. 1994; Barré et al. 2010).

We conclude that feral cat predation is not yet a major issue for kagu conservation. However, we recommend multi-species management to mitigate the direct and indirect threats of invasive mammals (Griffiths 2011) to the remaining kagu populations, still fragile and confined to limited areas.

Acknowledgments

We are very grateful to civil and provincial authorities for allowing us to conduct this research in Parc Provincial de la Rivière Bleue and Parc des Grandes Fougères. The authors sincerely acknowledge the Société Calédonienne d'Ornithologie (SCO) and the Parc Zoologique et Forestier

(PZF) for kagu corpses used as reference materials for this study. The experiments comply with the current laws of France and New Caledonia (permission for sampling protocol n°2155-2012/ARR/DENV). We thank Hélène de Méringo for helping during fieldwork and trophic analyses. Our thanks to M. Sweetko for English language revision.

References

- Avibase 2017. The world bird database. Available from <http://avibase.bsc-eoc.org/> (accessed March 2017).
- Barré N, Tron F, Chartendraul V, Okahisa Y, Sato NJ, Legault A, Theuerkauf J 2013. Breeding seasons of landbirds in New Caledonia. *The Wilson Journal of Ornithology* 125: 384–398.
- Barré N, Chazeau J, Jourdan H 2010. La faune des milieux sur roches ultramafiques. In: L'Huilier L, Jaffré T, Wulff A eds. *Mines et environnement en Nouvelle-Calédonie: les milieux sur substrats ultramafiques et leur restauration*. Editions IAC, Nouméa, Pp. 105–128.
- Beauvais M-L, Coléno A, Jourdan H 2006. Invasive species in the New Caledonian archipelago: a major economic and environmental hazard. Collection Expertise Collégiale, IRD Editions, Paris.
- BirdLife International 2016. *Rhynochetos jubatus*. The IUCN Red List of Threatened Species 2016: e.T22692211A93341677. <http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22692211A93341677.en> (accessed February 2017).
- BirdLife International 2017. IUCN Red List for birds. <http://www.birdlife.org> (accessed March 2017).
- Boissenin M 2012. Rapport d'état d'avancement relatif à la mise en œuvre du plan d'action pour la sauvegarde du Cagou. Technical report. Société Calédonienne d'Ornithologie, Nouméa.
- Bonnaud E, Bourgeois K, Vidal E, Kayser Y, Tranchant Y, Legrand J 2007. Feeding ecology of a feral cat population on a small Mediterranean island. *Journal of Mammalogy* 88: 1074–1081.
- Bonnaud E, Medina FM, Vidal E, Nogales M, Tershy B, Zavaleta E, Donlan CJ, Keitt B, Le Corre M, Horwath SV 2011. The diet of feral cats on islands: a review and a call for more studies. *Biological Invasions* 13: 581–603.
- Bonnaud E, Palmas P, Bourgeois K, Ollier S, Zarzoso-Lacoste D, Vidal E 2015. Island specificities matter: cat diet differs significantly between islands of a major breeding archipelago for a vulnerable endemic seabird. *Biological Invasions* 17: 2927–2941.
- Burbidge AA, McKenzie NL 1989. Patterns in the modern decline of Western Australia's vertebrate fauna: causes and conservation implications. *Biological Conservation* 50: 143–198.
- Carthey AJR, Banks PB 2014. Naïveté in novel ecological interactions: lessons from theory and experimental evidence. *Biological Reviews* 89: 932–949.
- Cohic F 1950. Activité saisonnière de la faune économique néo-calédonienne. *Revue Française d'Entomologie* 17: 81–87.
- Dickman CR 1996. Impact of exotic generalist predators on the native fauna of Australia. *Wildlife Biology* 2: 185–195.
- Doherty TS, Davis RA, van Etten EJB, Algar D, Collier N, Dickman CR, Edwards G, Masters P, Palmer R, Robinson S 2015. A continental-scale analysis of feral cat diet in Australia. *Journal of Biogeography* 42: 964–975.

- Doherty TS, Glen AS, Nimmo DG, Ritchie EG, Dickman CR 2016. Invasive predators and global biodiversity loss. *Proceedings of the National Academy of Sciences* 113: 11261–11265.
- Driscoll CA, Menotti-Raymond M, Roca AL, Hupe K, Johnson WE, Geffen E, Harley EH, Delibes M, Pontier D, Kitchener AC, Yamaguchi N, O'Brien SJ, Macdonald DW 2007. The near eastern origin of cat domestication. *Science* 317: 519–523.
- Fawcett T 2006. An introduction to ROC analysis. *Pattern Recognition Letters* 27: 861–874.
- Fielding AH, Bell JF 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24: 38–49.
- Forsyth DM, Woodford L, Moloney PD, Hampton JO, Woolnough AP, Tucker M 2014. How does a carnivore guild utilise a substantial but unpredictable anthropogenic food source? Scavenging on hunter-shot ungulate carcasses by wild dogs/dingoes, red foxes and feral cats in south-eastern Australia revealed by camera traps. *PLoS ONE* 9: e97937.
- Goltz DM, Hess SC, Brinck KW, Banko PC, Danner RM 2008. Home range and movements of feral cats on Mauna Kea, Hawai'i. *Pacific Conservation Biology* 14: 177–184.
- Griffiths R 2011. Targeting multiple species – a more efficient approach to pest eradication. In: Veitch CR, Clout MN, Towns DR eds. *Island invasives: eradication and management*. Gland, Switzerland, IUCN. Pp. 172–176.
- Guilbert E, Baylac M, Bonnet de Laborgne L 1994. Canopy arthropod diversity of New Caledonian primary forest sampled by fogging: preliminary results. *Memoirs of the Queensland Museum* 36: 77–85.
- Guilbert E 1997. Arthropod biodiversity in the canopy of New Caledonian forests. In: Stork NE, Adis J, Didham RK eds. *Canopy arthropods*. London, Chapman & Hall. Pp. 265–277.
- Gula R, Theuerkauf J, Rouys S, Legault A 2010. An audio/video surveillance system for wildlife. *European Journal of Wildlife Research* 56: 803–807.
- Hunt GR 1997. Ecology and conservation of the kagu *Rhynochetos jubatus* of New Caledonia. PhD thesis, Massey University.
- Hunt GR, Hay R, Veltman CJ 1996. Multiple kagu *Rhynochetos jubatus* deaths caused by dog attacks at a high-altitude study site on Pic Ningua, New Caledonia. *Bird Conservation International* 6: 295–306.
- Ibanez T, Munzinger J, Dagostini G, Hequet V, Rigault F, Jaffré T, Birnbaum P 2014. Structural and floristic diversity of mixed tropical rain forest in New Caledonia: new data from the New Caledonian Plant Inventory and Permanent Plot Network (NC-PIPPN). *Applied Vegetation Science* 17: 386–397.
- Isnard S, L'huillier L, Rigault F, Jaffré T 2016. How did the ultramafic soils shape the flora of the New Caledonian hotspot? *Plant Soil* 403: 53–76.
- Krebs CJ 1999. *Ecological methodology*. Addison Wesley Education Publishers, New York, United States of America.
- Le Goff A, Brescia F 2011. Inventaire des gîtes à mégachiroptères et des populations de bulimes dans les parcs et réserves de la Province Sud. IAC, Institut Agronomique néo-Calédonien. 99 p.
- Léotocart Y, Salas M 1997. Spatial organisation and breeding of kagu *Rhynochetos jubatus* in Rivière Bleue Park, New Caledonia. *Emu* 97: 97–107.
- Loyd KAT, Hernandez SM, Carroll JP, Abernathy KJ, Marshall GJ 2013. Quantifying free-roaming domestic cat predation using animal-borne video cameras. *Biological Conservation* 160: 183–189.
- McLennan JA, Potter MA, Robertson HA, Wake GC, Colbourne R, Dew L, Joyce L, McCann AJ, Miles J, Miller PJ, Reid J 1996. Role of predation in the decline of kiwi *Apteryx* spp., in New Zealand. *New Zealand Ecological Society* 20: 27–35.
- McRuer DL, Gray LC, Horne LA, Clark EE Jr 2017. Free-roaming cat interactions with wildlife admitted to a wildlife hospital. *Journal of Wildlife Management* 81: 163–73.
- Medina FM, Bonnaud E, Vidal E, Tershy BR, Zavaleta ES, Donlan JC, Keitt BS, Le Corre M, Horwath SV, Nogales M 2011. A global review of the impacts of invasive cats on island endangered vertebrates. *Global Change Biology* 17: 3503–3510.
- Medina FM, Bonnaud E, Vidal E, Nogales M 2014. Underlying impacts of invasive cats on islands: not only a question of predation. *Biodiversity Conservation* 23: 327–342.
- Meriot J-M, Manaute J, Bourget R 2009. Rapport évolution de la population de cagous sauvages dans le parc provincial de la Rivière bleue de 1982 à 2009. Unpublished report. Province Sud/DENV/PPRB, Nouméa.
- Moseby KE, Read J 2006. The efficacy of feral cat, fox and rabbit exclusion fence designs for threatened species protection. *Biological Conservation* 127: 427–437.
- Myers P, Espinosa R, Parr CS, Jones T, Hammond GS, Dewey TA 2017. The animal diversity web. University of Michigan. Available from <http://animaldiversity.org> (accessed January 2017).
- Nogales M, Vidal E, Medina FM, Bonnaud E, Tershy BR, Campbell KJ, Zavaleta ES 2013. Feral cats and biodiversity conservation: the urgent prioritization of island management. *Bioscience* 63: 804–810.
- Palmas P, Jourdan H, Rigault F, Debar L, De Meringo H, Bourguet E, Mathivet M, Lee M, Adjouhgniope R, Papillon Y, Bonnaud E, Vidal E 2017. Feral cats threaten the outstanding endemic fauna of the New Caledonia biodiversity hotspot. *Biological Conservation* 214: 250–259.
- R Core Team (2014). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.
- Roots C 2006. *Flightless birds*. Greenwood guides to the animal world. Westport, Greenwood Press. 248 p.
- Rouys S, Theuerkauf J 2003. Factors determining the distribution of introduced mammals in nature reserves of the southern province, New Caledonia. *Wildlife Research* 30: 187–191.
- Rouys S 2008. *Ecologie des rats et leur impact sur le cagou et la perruche à front rouge en forêt humide et dans le maquis de Nouvelle-Calédonie*. Thèse de doctorat, Université de Nouvelle-Calédonie, Nouméa. 242 p.
- Sarasin F 1913. Die Vogel Neu-Kaledoniens und der Loyalty-Inseln. In: Sarasin F, Roux R eds. *Nova Caledonia, Zoologie, Vol. 1*. Wiesbaden C.W. Kriedels Verlag. Pp. 55–60.
- Steadman DW 2006. *Extinction and biogeography of tropical Pacific birds*. Chicago, University of Chicago Press. 480 p.
- Theuerkauf J, Rouys S 2008. Etude de l'impact des mammifères introduits et de la perte d'habitat sur les oiseaux endémiques

- de Nouvelle-Calédonie. CEPA Magazine 18: 13–16.
- Theuerkauf J, Rouys S, Mériot JM, Gula R 2009. Group territoriality as a form of cooperative breeding in the flightless kagu of New Caledonia. *Auk* 126: 371–375.
- Theuerkauf J, Haneda T, Okahisa Y, Sato Nj, Rouys, Bloc H, Ueda K, Watanabe I, Kuehn R, Gula R 2017. Elevated concentrations of naturally occurring heavy metals inversely correlate with reproductive output and body mass of the kagu *Rhynochetos jubatus*. *Ibis* 159: 580–587.
- Turner DC, Bateson PPG 2014. *The domestic cat: the biology of its behaviour*. 3rd edition. Cambridge, Cambridge University Press. 256 p.
- Warner DW 1948. The present status of the kagu *Rhynochetos jubatus* on New Caledonia. *Auk* 65: 287–288.
- Woinarski JCZ, Woolley LA, Garnett ST, Legge SM, Murphy BP, Lawes M, Comer S, Dickman CR, Doherty TS, Edwards G, Nankivill A, Palmer R, Paton D 2017. Compilation and traits of Australian bird species killed by cats. *Biological Conservation* 216: 1–9.
- Zarzoso-Lacoste D, Bonnaud E, Corse E, Gilles A, Meglecz E, Costedoat C, Gouni A, Vidal E 2016. Improving morphological diet studies with molecular ecology: an application for invasive mammal predation on island birds. *Biological Conservation* 193: 134–142.

Editorial board member: Al Glen

Received 5 December 2018; accepted 9 July 2019

Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Figure S1. Previous (a) and current (b) banknote of French Pacific territories showing pictures of kagu.

Table S1. List of flightless bird species extinct due (at least partially) to cat predation.

The New Zealand Journal of Ecology provides supporting information supplied by the authors where this may assist readers. Such materials are peer-reviewed and copy-edited but any issues relating to this information (other than missing files) should be addressed to the authors.

Supplementary material

Figure S1. Previous (a) and current (b) banknote of French Pacific territories showing pictures of Kagu (1000XPF = 8.99 USD).



Table S1. List of flightless bird species extinct due (at least partially) to cat predation (derived from Doherty et al. 2016).

Extinct bird species	Synonyms	References (see below)
<i>Aphanapteryx bonasia</i>		a
<i>Cabalus modestus</i>		b
<i>Gallinula nesiotis</i>		c
<i>Hypotaenidia dieffenbachii</i>	<i>Gallirallus dieffenbachii</i>	d
<i>Hypotaenidia owstoni</i>		e
<i>Hypotaenidia pacifica</i>		f
<i>Hypotaenidia poeciloptera</i>	<i>Nesoclopeus poecilopterus</i>	g
<i>Mundia elpenor</i>		h
<i>Pezophaps solitaria</i>		i
<i>Traversia lyalli</i>		j
<i>Upupa antaios</i>		k
<i>Zapornia sandwichensis</i>		l
<i>Dryolimnas augusti</i> *		m
<i>Porphyrio paepae</i> *		n

* flightless character probable only

- a. BirdLife International 2016. *Aphanapteryx bonasia*. The IUCN Red List of Threatened Species 2016: e.T22728884A94999673. <http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22728884A94999673.en>. (accessed April 2017).
- b. Tennyson AJD 2013. Chatham Island rail. In: Miskelly CM ed. New Zealand birds online. Available from www.nzbirdsonline.org.nz
- c. Beintema AJ 1972. The history of the Island Hen *Gallinula nesiotis*, the extinct flightless gallinule of Tristan da Cunha. Bulletin of the British Ornithologists' Club 92:106–113.
- d. Trewick SA 1997. Sympatric flightless rails *Gallirallus dieffenbachii* and *G. modestus* on the Chatham Islands, New Zealand; morphometrics and alternative evolutionary scenarios. Journal of the Royal Society of New Zealand 27: 451–464.
- e. BirdLife International 2016. *Hypotaenidia owstoni*. The IUCN Red List of Threatened Species 2016: e.T22692441A93353974. <http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22692441A93353974.en>. (accessed April 2017).
- f. BirdLife International 2016. *Hypotaenidia pacifica*. The IUCN Red List of Threatened Species 2016: e.T22692450A93354380. <http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22692450A93354380.en>. (accessed April 2017).
- g. Taylor B 2017. Bar-winged rail (*Nesoclopeus poecilopterus*). In: del Hoyo J, Elliott A, Sargatal J, Christie DA, de Juana E eds. Handbook of the birds of the world alive. Lynx Edicions, Barcelona.
- h. BirdLife International 2012. *Mundia elpenor*. The IUCN Red List of Threatened Species 2012: e.T22728746A38307793. <http://dx.doi.org/10.2305/IUCN.UK.2012-1.RLTS.T22728746A38307793.en> (accessed April 2017).
- i. Livezey BC 1993. An ecomorphological review of the dodo (*Raphus cucullatus*) and solitaire (*Pezophaps solitaria*), flightless Columbiformes of the Mascarene Islands, Journal of Zoology 230: 247–292.
- j. Southey I 2013. Lyall's wren. In: Miskelly CM ed. New Zealand birds online. Available from www.nzbirdsonline.org.nz
- k. BirdLife International 2016. *Upupa antaios*. The IUCN Red List of Threatened Species 2016: e.T22728670A94993541. <http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22728670A94993541.en>. (accessed April 2017).
- l. Olson SL 1999. Hawaiian rail *Zapornia sandwichensis*. The Cornell Lab of Ornithology, Bird of North America. Available from <https://birdsna.org/Species-Account/bna/species/hawrai/introduction> (accessed April 2017).
- m. BirdLife International 2016. *Dryolimnas augusti*. The IUCN Red List of Threatened Species 2016: e.T62258591A95193478. <http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T62258591A95193478.en>. (accessed April 2017).
- n. Kirchman JJ, Steadman DW 2006. New Species of rails (Aves: Rallidae) from an Archaeological Site on Huahine, Society Islands. Pacific Science 60: 281–297.