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# Invasive rodents, an overlooked threat for skinks in a tropical island hotspot of biodiversity

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**Abstract:** Squamata are one of the most threatened groups among island vertebrates, facing high pressure from exotic species. However, the contribution of small terrestrial reptiles in invasive rodents’ diet remains poorly investigated, partly because of the lack of tools for accurately identifying chewed prey fragments in gut contents. The New Caledonia archipelago (South Pacific) hosts an exceptional terrestrial squamata fauna (105 species, 91.6% endemic) that are faced with many invasive species (rodents, feral cats, feral pigs, ants) and strong human pressures. Our study aimed to evaluate the frequency of occurrence of endemic skink remains by gut content analysis of two species of invasive rodents. Four rodent trapping sessions were implemented at two ultramafic sites and for two distinct habitats (closed canopy forest and open shrubland habitat). A total of 284 rats were trapped from two species (the ship rat *Rattus rattus* and the Pacific rat *R. exulans*) over 1200 trap nights. Combined analysis of stomach and caecum contents provided far more information than traditional stomach analysis alone. Analyses showed that 15.9% of rat samples included remains of at least 12 different skink species out of the 23 present. Six species are classified as threatened by the IUCN, the most endangered being *Marmorosphax taom* (CR) and *Kanakysaurus viviparus* (EN). This study provides new prospects for the assessment of invasive rodent impacts and new insights into the respective impacts of two sympatric invasive rodent species on native skinks.

**Keywords:** diet analysis; endemic skinks; island conservation; *Rattus exulans*; *Rattus rattus*

## Introduction

The main causes of biodiversity loss are now well identified: habitat fragmentation and destruction, invasive species and climate change (Sala et al. 2000; Pereira et al. 2012). Sax and Gaines (2008) and Tershy et al. (2015) have shown that, over the last 500 years, the majority of documented plant or vertebrate extinctions have occurred on islands. This pattern is especially true of extinctions caused by exotic species (Bellard et al. 2016). Walsh et al. (2012) showed that species richness and endemism increase the impact of exotic species on islands.

Rodents are among the most widespread commensal invasive species. They have been introduced to over 80% of the world’s islands, with many harmful impacts (Atkinson 1985). We know that these opportunistic species are responsible for species depletion and/or extinction worldwide, especially in insular ecosystems (Courchamp et al. 2003; Harper & Bunbury 2015). Invasive rodents can severely affect turtles and seabirds (Caut et al. 2008; Jones et al. 2008), amphibians (McCallum 1986) and mammals (Hanna & Cardillo 2014; Smith & Banks 2014). Several studies have shown that *Rattus rattus* is the most damaging rodent for island ecosystems (Jones et al. 2008; Ruffino et al. 2009; Traveset et al. 2009; Banks & Hughes 2012; Shiels et al. 2014), and introduction of this species is followed by the greatest number of declines or extinctions of native island biota, according to Towns et al. (2006).

Case and Bolger (1991) revealed that island reptiles are highly threatened by introduced species, especially on islands that were predator-free before introductions. They found that rodents consume reptile eggs, young, and even adults,

depending on prey size. These authors record several island reptile declines (lizards, tuatara) induced by the introduction of *R. rattus*, *R. exulans* or *R. norvegicus*. The blue-tailed skink (*Cryptoblepharus egeriae*) is assumed to have declined because of rodent predation on Christmas Island (Low et al. 2013), which is also the case for the endemic Belize leaf-toed gecko (*Phyllodactylus insularis*) on Half Moon Caye (Meerman 1996) and the whiptail lizard (*Cnemidophorus vanzoi*) on St Lucia (John 1999). On Rodrigues Island, large gecko species (*Phelsuma edwardnewtoni* and *P. gigas*) were devastated after rat introductions (Vinson & Vinson 1969). The only two native lizards of Lord Howe Island (*Phyllodactylus guentheri* and *Leiopisma lichenigerum*) are also known to have declined after the introduction of the black rat *R. rattus* in 1918 (Cogger 1971). Several New Zealand skink and gecko species are now confined to rat-free offshore islands, but bone deposits indicate that they were widespread on the mainland before rats were introduced (Worthy 1987). Furthermore, in New Zealand, skink and gecko species showed habitat plasticity after rat introduction (Whitaker 1978; Hoare et al. 2007) or removal (Towns 1991, 1996). More recently, Harper and Bunbury (2015) reviewed the impacts of invasive rats on islands, pointing out how herpetofauna features in the rodent diet. Even though island reptile records pre-dating rat introduction are often unavailable, the studies mentioned above, together with historical observations, point to rodents and other introduced species being important threats to the maintenance of island reptile communities over time. Tropical regions and oceanic islands have the highest proportion of threatened squamata species, according to Böhm et al. (2013). In particular, New

Caledonia is considered by these authors as a world centre of threatened reptile species.

New Caledonia is one of the world's 35 biodiversity hotspots (Myers et al. 2000; Mittermeier et al. 2011). Located east of Australia in the Southwest Pacific, this tropical island hosts an outstanding squamata fauna, including 63 scincidae species (61 endemic), 36 diplodactylidae gecko (all endemic) and six geckonidae gecko species. This herpetofauna is of high biodiversity concern, given the exceptional endemism rates (91.6%) and the unfavourable conservation status for most of the species, with 66 taxa considered as endangered (CR, EN or VU) (Whitaker & Sadlier 2011; Bauer et al. 2012a, b; Sadlier et al. 2012, 2013, 2014a, b, c, d). This unique herpetofauna is facing high pressure from introduced alien species and human-induced habitat disturbances. Among invasives, four rodent species (*R. rattus*, *R. exulans*, *R. norvegicus* and *Mus musculus*) introduced into New Caledonia may be responsible for a significant disruption of native herpetofauna (Beauvais et al. 2006). The Pacific rat (*R. exulans*) was introduced into New Caledonia by Melanesian people between 2400 and 3300 years before present (Balouet 1984, 1987). The ship rat (*R. rattus*), brown rat (*R. norvegicus*) and house mouse (*M. musculus*) arrived more recently with European settlers around 1850 (Pascal et al. 2006). *Rattus rattus* and *R. exulans* are now widely distributed throughout the Caledonian archipelago (Rouys & Theuerkauf 2003; Pascal et al. 2006) and are often sympatric, a situation widespread in Pacific islands but not known outside the region.

A better understanding of introduced rodent impacts on communities of squamata, especially in New Caledonia, as suggested by Bauer and Sadlier (2000), would appear to be vital to squamata conservation. In particular, the contribution of small terrestrial reptiles in invasive rodents' diet remains poorly investigated. The lack of experimental studies demonstrating rodent impacts and response to control methods contribute to explaining this lack of information.

The present study investigates the impacts of introduced rodents (ship rat and Pacific rat) on terrestrial reptiles. We explore a more efficient protocol of diet analysis to assess lizard consumption by rats, going beyond traditional analysis of stomach contents alone, as suggested in similar studies (Lewis et al. 2011). Using our own lab reference collection and an associated determination key of reptile remains, we evaluate reptile consumption occurrences. Finally, we considered management options in line with the conservation status of specific consumed species, from full removal to exclusion fencing.

## Materials and methods

### Study sites

Two distinct sites were selected for this study, both on ultramafic substrates (Fig. 1). On each site, rodents were sampled in two contrasting vegetation types: dense and open forest. The Goro site is located near Goro village, in the southern province of New Caledonia (22° 10' 03" S; 166° 55' 36" E). Fifteen skink (14 endemic) and 14 gecko (11 endemic) species are known to be present at this site (Table 1), of which seven and three species respectively are listed as threatened on the IUCN red list. The dense forest we selected is dominated by *Arillastrum gummiferum*, hosting 90% endemic plant species, with a canopy height of around 20 m (Jaffré et al. 2004). The open forest is

dominated by *Gymnostoma deplancheanum* and *Tristaniopsis* spp., rising to a height of 6–10 metres (Jaffré et al. 2003).

The Tiebaghi site is in the northern province of New Caledonia (20° 33' 43" S, 164° 15' 43" E) on Tiebaghi Mountain. Thirteen skink (all endemic) and eight gecko species (five endemic) are present, of which four and three species respectively are listed as threatened (Table 1). The dense forest is in a talweg and rises to a height of 20–25 m. The open forest habitat hosts few endemic arboreal species, with a canopy around 10 m and several endemic shrub species (Dagostini et al. 1997).

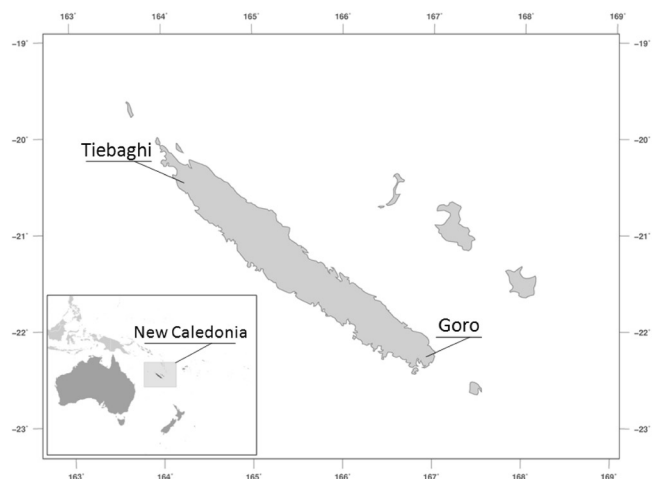
### Rodent trapping method

As in Cunningham and Moors (1996), rodents were caught using lethal traps ('Trapper' snap traps for rats and 'E' mouse traps for mice, Pest Management Services, NZ). Trapping sessions involved 25 pairs of rat and mouse traps set at 25 m intervals along a 625 m transect in each of the habitats. The traps were baited with cheese (cheddar) and peanut butter. The mouse traps were placed under plastic tunnels to reduce the risk to non-target species.

We trapped rodents twice a year at each site in both forest types. Overall, four trapping sessions were conducted at each site and habitat. Trapping sessions in Goro were held in April and August 2013, and in January and March 2014. Trapping sessions in Tiebaghi were held in February, June and October 2013, and February 2014. Each trapping session lasted 4 days, i.e. 3 consecutive nights. Traps were baited just before nightfall and checked every morning. Following Cunningham and Moors (1996), each rat caught was weighed, sexed and measured for head-body length, tail length and reproductive status.

### Rodent diet analysis

The digestive tracts of all the rodents caught were collected in the field, preserved in 70% ethyl alcohol (Sugihara 1997) and frozen for further laboratory analysis. The contents were analysed according to the method described in Abbas (1988). Stomach and caecum were opened by incising the convex surface; the interior was scraped and the contents were poured into a 0.5 mm sieve. The contents were rinsed with tap water until the filtrate appeared clear, then placed in a Petri dish with



**Figure 1.** Location of New Caledonia and our two study sites on the New Caledonian mainland.

**Table 1.** List of squamata recorded in each studied site. IUCN status according to Whitaker and Sadlier (2011); Bauer et al. (2012); Sadlier et al. (2013, 2014, 2015). Habitat: F: forest; MP: forested shrubland; M: Maquis shrubland. Status: E: endemic species; EE: endemic genera; A: native species; I= introduced species. Highlighted species were preyed-upon in this study.

<b>Scincidae</b>		Status	IUCN	Habitat	Tiéb.	Goro
<i>Caesoris novaecaledoniae</i>	(Parker) 1926	EE	LC	<b>M</b>	+	
<i>Caledoniscincus aquilonius</i>	Sadlier, Bauer & Colgan 1999	E	NT	<b>F, MP</b>	+	
<i>Caledoniscincus atropunctatus</i>	(Roux) 1913	A	LC	<b>F, MP</b>	+	
<i>Caledoniscincus auratus</i>	Sadlier, Bauer & Colgan 1999	E	EN	<b>F, MP</b>	+	
<i>Caledoniscincus austrocaledonicus</i>	(Bavay) 1869	E	LC	<b>F, MP</b>	+	+
<i>Caledoniscincus festivus</i>	(Roux) 1913	E	LC	<b>F, MP</b>	+	+
<i>Caledoniscincus haplorhinus</i>	(Günther) 1872	E	LC	<b>M</b>	+	+
<i>Caledoniscincus notialis</i>	Sadlier, Bauer, Wood, Smith & Jackman 2013	E	VU	<b>F, MP</b>		+
<i>Caledoniscincus pelletieri</i>	Sadlier, Whitaker, Wood & Bauer 2014	E	CR	<b>F, MP</b>	+	
<i>Cryptoblepharus novocaedonicus</i>	(Mertens) 1928	E	LC	<b>M</b>		+
<i>Epibator nigrofasciolatus</i>	(Peter) 1869	EE	LC	<b>F, MP, M</b>	+	+
<i>Graciliscincus shonae</i>	Sadlier 1986	EE	VU	<b>F, MP</b>		+
<i>Kanakysaurus viviparus</i>	Sadlier, Smith, Bauer & Whitaker 2004	EE	EN	<b>F, MP</b>	+	
<i>Lacertoides pardalis</i>	Sadlier, Shea & Bauer 1997	EE	VU	<b>M</b>		+
<i>Marmorosphax taom</i>	Sadlier, Smith, Bauer & Whitaker 2009	EE	CR	<b>F, MP</b>	+	
<i>Marmorosphax tricolor</i>	(Bavay) 1869	EE	LC	<b>F, MP</b>		+
<i>Nannoscincus mariei</i>	(Bavay) 1869	EE	VU	<b>F</b>		+
<i>Phymasaurus tillieri</i>	Ineich & Sadlier 1991	EE	NT	<b>MP, M</b>		+
<i>Phoboscincus garnieri</i>	(Bavay) 1869	EE	LC	<b>F, MP</b>	+	+
<i>Sigaloseps deplanchei</i>	(Bavay) 1869	EE	NT	<b>F, MP</b>		+
<i>Simiscincus aurantiacus</i>	Sadlier & Bauer 1997	EE	VU	<b>F, MP</b>		+
<i>Tropidoscincus boreus</i>	Sadlier & Bauer 2000	EE	LC	<b>M, MP, F</b>	+	
<i>Tropidoscincus variabilis</i>	(Bavay) 1869	EE	LC	<b>MP, M</b>		+
					<b>13</b>	<b>15</b>
<b>Diplodactylidae</b>						
<i>Bavayia cyclura</i>	(Günther) 1872	EE	DD	<b>F, MP</b>		+
<i>Bavayia geitaina</i>	Wright, Bauer & Sadlier 2000	EE	VU	<b>F, MP</b>		+
<i>Bavayia goroensis</i>	Bauer, Jackman, Sadlier, Shea & Whitaker 2008	EE	EN	<b>F</b>		+
<i>Bavayia robusta</i>	Wright, Bauer & Sadlier 2000	EE	LC	<b>F</b>		+
<i>Bavayia sauvagii</i>	(Boulenger) 1883	EE	DD	<b>F, MP</b>		+
<i>Bavayia septuiclavis</i>	Sadlier 1989	EE	NT	<b>F, MP</b>		+
<i>Correlophus sarasinorum</i>	(Roux) 1913	EE	EN	<b>F</b>		+
<i>Dierogecko nehoueensis</i>	Bauer, Jackman, Sadlier, Whitaker 2006	EE	CR	<b>F, MP</b>	+	
<i>Eurydactylodes agricolae</i>	Henkel & Böhme 2001	EE	NT	<b>F, M, MP</b>	+	
<i>Eurydactylodes symmetricus</i>	(Andersson) 1908	EE	EN	<b>F, MP</b>		+
<i>Eurydactylodes vieillardi</i>	(Bavay) 1869	EE	NT	<b>F, MP</b>		+
<i>Mniarogekko jalu</i>	Bauer, Whitaker, Sadlier & Jackman 2012	EE	EN	<b>F, MP</b>	+	
<i>Oedodera marmorata</i>	Bauer, Jackman, Sadlier, Whitaker 2006	EE	CR	<b>F</b>	+	
<i>Rhacodactylus auriculatus</i>	(Bavay) 1869	EE	LC	<b>MP, M</b>	+	+
<i>Rhacodactylus leachianus</i>	(Cuvier) 1829	EE	LC	<b>F, MP</b>		+
					<b>5</b>	<b>11</b>
<b>Gekkonidae</b>						
<i>Hemidactylus frenatus</i>	Schlegel in Duméril & Bibron 1836	I	LC	<b>M</b>	+	+
<i>Hemidactylus garnotii</i>	Duméril & Bibron 1836	I	LC	<b>M</b>	+	+
<i>Lepidodactylus lugubris</i>	(Duméril & Bibron) 1836	I	LC	<b>M</b>	+	+
					<b>3</b>	<b>3</b>

70% alcohol and examined under a dissecting microscope at 10 x magnification.

We first analysed the entire digestive tracts of 20 individuals (five individuals of each sex per species) in order to determine which organs provided the most information on skink consumption. Four rats contained skink remains: three scales were found in small intestines, six in colons, 10 in stomachs and more than 60 in caecums. Each time we found scales in a gut, they were present in at least the stomach and the caecum. Therefore we focused our analysis on both stomach and caecum contents (separately) in order to maximize the probability of detecting reptile remains in the most time-efficient way.

Remains found in stomach and caecum were classified into nine categories: plants, insects, crustaceans, gastropods, earthworms, birds, parasites, geckos and skinks. Particular attention was given to the identification of skink remains up to species level, using our laboratory reference collection of skink scales. This collection consists of scales extracted from identified skinks and mounted for observation under microscope. We also used a skink scale determination key developed by our team during this project (Jourdan et al. 2014). Essentially, identifications were based on small groups of well-preserved scales sharing the same morphological patterns.

### Data analysis

For each site, we calculated a relative abundance index based on the number of rats trapped during 100 trap nights, following the method described in Nelson and Clark (1973). All traps were checked every morning of each trapping session and the 'state' of the trap was recorded. If it was closed without a rat or still open without bait, the trap was considered as active for half a night only. The relative abundance index was then corrected by subtracting half a trap night for each of these traps.

For each item found during the diet analysis, we calculated an occurrence frequency by species and organ (stomach or caecum) as the number of individuals/organs containing the item divided by the total number of individuals analysed. We then related these frequencies to the skink conservation status, in order to determine those skink species potentially more sensitive to predation by introduced rodents.

We used the  $\chi^2$  test of independence in R version 3.0.1 (R Development Core Team 2008) to determine whether skink remains occurrence frequencies differed between sites, habitats, rat species, sexes and maturity levels. When there were fewer than five samples, the Fisher exact test was used (Fisher & Yates 1963).

### Results

A total of 135 Pacific rats (*R. exulans*) and 50 ship rats (*R. rattus*) were captured during the four trapping sessions at the Goro site, while 35 individuals of *R. exulans* (Re) and 63 *R. rattus* (Rr) were trapped at the Tiebaghi site (Table 2). The relative abundance index for Pacific rats was higher at Goro than at Tiebaghi ( $\chi^2 = 12.7$ ,  $df = 1$ ,  $p = 3.6 \times 10^{-4}$ ), as shown in Figure 2. We recorded 24 Re.100 trap night<sup>-1</sup> and 6 Re.100 trap night<sup>-1</sup> at the two sites respectively. For ship rats, no significant difference was found between the two sites (11 Rr.100 trap night<sup>-1</sup> in Goro; 12 Rr.100 trap night<sup>-1</sup> in Tiebaghi). A total of 283 gut samples were taken for diet analysis (one rat was too damaged to be analysable). No mice were trapped at any site during this study.

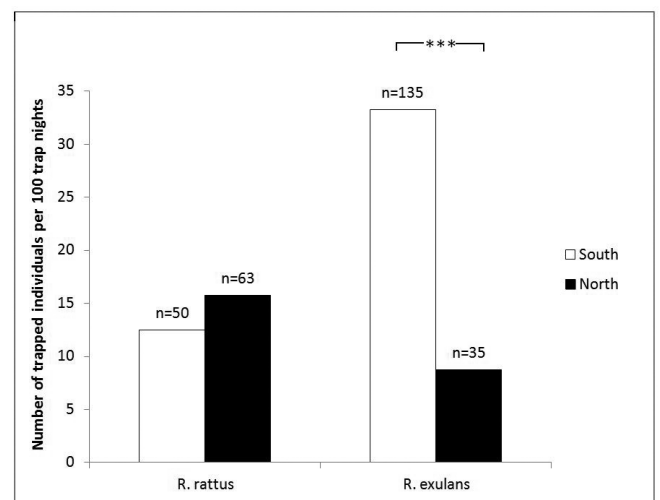
Analysis of both stomachs and caecums led to significantly better detection of skink remains than did stomach analysis alone ( $\chi^2 = 9.9$ ;  $df = 1$ ;  $p = 0.0017$ ). Combined analysis of these two digestive organs improved our detection capacity twofold compared with the 'classical' approach focused on the stomach alone (Fig. 3). Independent analyses of these two organs also suggest that caecums contained more skink remains than stomachs ( $\chi^2 = 6.04$ ;  $df = 1$ ;  $p = 0.014$ ). Full results of the diet analysis are presented in Table 3. Plant items were present in 96.5% and 48.2% of ship rats and Pacific rats, respectively. Insects were found in inverse proportion: 93.5% in Pacific rats and 56.6% in ship rats. Feather remains were found in ship rats only (n=8), four cases at each site.

Squamata remains were found in 19.1% of analysed rats (n=283, Table 3). Of the rats, 15.9% had fed on skinks and 4.6% on geckos; 86% had consumed only one skink species, 13.9% had fed on two species. One Pacific rat contained remains of three species and one ship rat contained remains of seven skink species. No significant differences in skink predation by rats were found between the two sites ( $\chi^2 = 0.02$ ;  $df = 1$ ;  $p = 0.89$ ), but skink consumption by the Pacific rat (18.2%; n=170) was slightly more frequent compared with ship rat (11.5%; n=113;  $\chi^2 = 2.72$ ;  $df = 1$ ;  $p = 0.099$ ). Rodents' maturity, sex and habitat did not significantly influence skink consumption rate (all analyses in Appendix S1 in Supplementary Material).

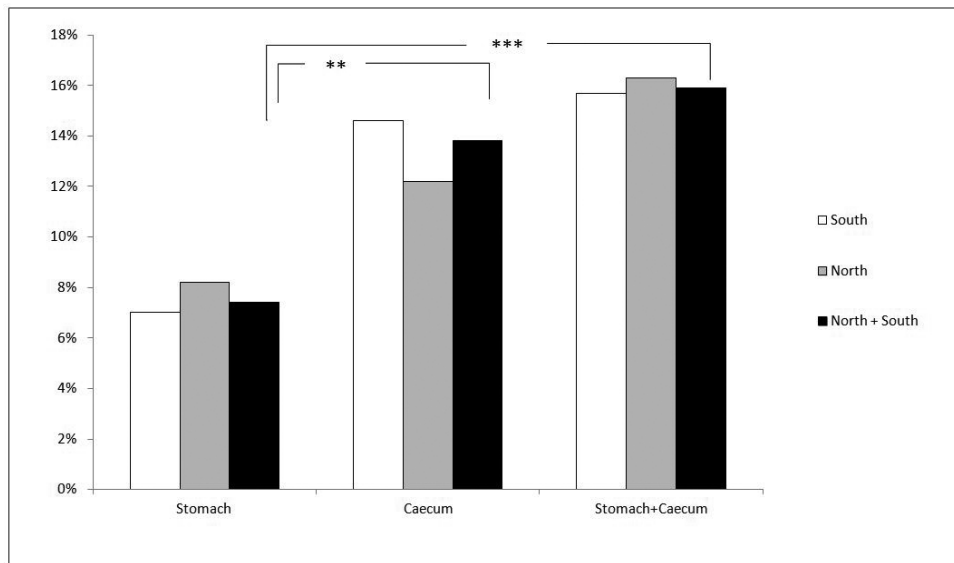
We were able to identify 91% of detected preyed skink individuals at species level. In this study, at least 12 skink

**Table 2.** Frequency of occurrence (in %) of skink remains in the digestive tracts (both stomach and caecum) of ship rats (*R. rattus*) and Pacific rats (*R. exulans*). Percentages were calculated dividing the number of rat samples that contained skink remains by the corresponding sample size (n). Split percentages were rounded to one decimal place.

	<i>Rattus exulans</i>	<i>Rattus rattus</i>	Total
<b>Tiebaghi</b>	22.9 % (n=35)	12.7 % (n=63)	16.3% (n=98)
<b>Goro</b>	17.8 % (n=135)	10 % (n=50)	15.7% (n=185)
<b>Total</b>	18.8 % (n=170)	11.5 % (n=113)	<b>15.9% (n=283)</b>



**Figure 2.** Results of trapping sessions, observed relative abundance indexes. \*\*\*:  $p < 0.01$ .



**Figure 3.** Frequency of occurrence of skink remains calculated for stomach and caecum contents analysed separately and together; \*\*:  $0.01 < p < 0.05$ , \*\*\*:  $p < 0.01$ .

**Table 3.** Percent frequency of occurrence of remains present in digestive tracts of ship rats (*R. rattus*) and Pacific rats (*R. exulans*) on the two study sites. As some skink species were restricted to one of the two study sites, occurrences were corrected with the number of rodents trapped at the corresponding site. \*Conservation status in IUCN red list. Sample sizes in brackets.

		Frequency of occurrence (no. ind.)		
		<i>R. rattus</i> (113)	<i>R. exulans</i> (170)	Total (283)
<b>Arthropods</b>		56.6(64)	<b>93.5</b> (159)	78.8(223)
<b>Plants</b>		<b>96.5</b> (109)	48.2(82)	67.5(191)
<b>Crustaceans</b>		2.7(3)	3.5(6)	3.2(9)
<b>Gastropods</b>		5.3(6)	2.9(5)	3.9(11)
<b>Earthworms</b>		1.8(2)	<b>20.6</b> (35)	13.1(37)
<b>Birds</b>		7.1(8)	-	2.8(8)
<b>Parasites</b>		77.0(87)	65.3(111)	70.0(198)
<b>Squamata</b>		16.8(19)	<b>20.6</b> (35)	19.1(54)
<b>Geckos</b>	<i>unidentified</i>	5.3(6)	4.1(7)	4.6(13)
<b>Skinks</b>		11.5(13)	18.2(32)	<b>15.9</b> (45)
	<i>Caledoniscincus atropunctatus</i>	1.8(2)	-	0.7(2)
	<i>Caledoniscincus austrocaledonicus</i>	0.9(1)	0.6(1)	0.7(2)
	<i>Caledoniscincus haplorhinus</i>	-	0.6(1)	0.4(1)
	<i>Caledoniscincus notialis</i>	0.9(1)	0.6(1)	0.7(2)
	<i>Caledoniscincus</i> sp.	0.9(1)	0.6(1)	0.7(2)
	<i>Graciliscincus shonae</i> (Vu)*	3.5(4)	<b>4.7</b> (8)	4.2(12)
	<i>Kanakysaurus viviparus</i> (En)	<b>3.5</b> (4)	<b>3.5</b> (6)	3.5(10)
	<i>Marmorosphax taom</i> (Cr)	0.9(1)	-	0.4(1)
	<i>Marmorosphax tricolor</i>	0.9(1)	7.6(13)	4.9(14)
	<i>Nannoscincus mariei</i> (Vu)	0.9(1)	1.2(2)	1.1(3)
	<i>Phasmosaurus tillieri</i>	0.9(1)	-	0.4(1)
	<i>Simiscincus aurantiacus</i> (Vu)	0.9(1)	2.4(4)	1.8(5)
	<i>Tropidoscincus variabilis</i>	0.9(1)	-	0.4(1)
	<i>unidentified</i>	0.9(1)	1.2(2)	1.1(3)

species were found to be preyed upon by rats (Table 3). Of these skink species 11 are endemic to New Caledonia and six are considered threatened, according to the IUCN red list (Table 3). Of the skink species known to be present, 38.5% and 46.6% were consumed at Tiebaghi and Goro sites, respectively. It is noteworthy that *Kanakysaurus viviparus* (endangered) and *Graciliscincus shonae* (vulnerable) are among the three most preyed-upon species by the two rat species. Our improved

diet analysis method also revealed predation upon three other vulnerable species at Goro site (*Caledoniscincus notialis*, *Simiscincus aurantiacus* and *Nannoscincus mariei*), although they were not among the most frequently consumed species. The analyses of caecal contents also allowed us to detect the presence of scales from *Marmorosphax taom* (critically endangered) in one ship rat from the Tiebaghi site.

## Discussion

### Rodent diet analysis

Analysis of caecal contents enabled us to determine rat diet over several food intakes more precisely than previous studies that focused on stomach analysis alone. Due to an estimated mean transit time of 12 hours in rats (Platel & Crinivasan 2001), stomachs only contain remains from very few food intakes, whereas the caecum, as a digestive dead-end, accumulates remains from multiple food intakes, mainly remains difficult to digest, like fibres, cuticle fragments or scales. Combined analysis of stomach and caecum allowed us to improve our skink remains detection capacity twofold. Therefore we recommend including the analysis of this digestive organ in future rodent diet analysis.

We found no skink head bones or jaws in any rat digestive contents. This observation may indicate that rats do not eat skink heads, as other skeletal parts were found in some samples. It also confirms the importance of developing a morphological identification tool based on body scales instead of bones to measure skink predation by rodents. DNA-based methods of diet analysis are increasingly popular and may significantly improve prey detection and identification in the rodent diet (Egeter et al. 2015; Zarzoso-Lacoste et al. 2016). But such methods require access to prey DNA, which is not possible in our context because of the rarity and patrimonial status associated with most Caledonian skink species. However, we were able to identify about 91% of detected preyed skink individuals to species level due to morphological analysis of scales, as recommended in Fuchs and Fuchs (2003). This approach is already used to control the reptile skin trade (Fuchs & Fuchs 2003) and we believe that the development of scale identification tools represents a major methodological improvement that will lead to better assessment of invasive rodent impacts on island endemic reptiles.

### Introduced rats' impact on native skinks

Our results show frequencies of occurrence of skink remains of about 18.2% for *R. exulans* and 11.5% for *R. rattus* samples. These frequencies of occurrence are higher than most previously reported in the literature on island rats' diet. In their work on Surprise Islet, located northwest of New Caledonia, Caut et al. (2008) found remains of one skink species (*C. haplorhinus*; Bauer et al. 1992; Sadlier et al. 1999) in 13% of the digestive tracts (stomach and droppings) of ship rats they caught and analysed. In Tasmania, Norman (1970) found remains of skinks in a single ship rat's stomach out of the 254 samples analysed. In 1990, Newman and McFadden (1990) analysed the stomachs of 134 Pacific rats on offshore islands in New Zealand: only three of them contained skink remains. More recently in Hawaiian forests, a diet study on *R. rattus*, *R. exulans* and *M. musculus* conducted by Shiels et al. (2013) revealed the complete absence of any skink remains in the stomachs analysed ( $n = 12\text{--}95$  individuals per species). Our result can be explained by the high skink species richness and abundance in the archipelago (Bauer & Sadlier 2000) combined with the likely improved estimation of predation rates in our study due to caecum content analysis.

For the two sites considered in this study, at least 12 different skink species among the 23 known to be present (c. 52%) were identified in the gut contents of rats. Six of these prey species are under threatened conservation status according to the IUCN Red List criteria (Whitaker & Sadlier 2011; Sadlier

et al. 2013). Two worth mentioning are *Marmorosphax taom* and *Kanakysaurus viviparus*, endemic and restricted to a few mountains in the north of the mainland. In addition, four vulnerable species are consumed by rats. These observations, based on only two sites over small areas in New Caledonia, underline the importance of taking introduced rat predation into consideration in plans for the conservation of native skink communities on islands.

We found no remains of the arboreal skink species *Epibator nigrofasciolatus* (which is a very common species in every habitat in New Caledonia) in either ship or Pacific rats. Moreover, geckonid (arboreal) remains were found as frequently in Pacific rats ( $n=7$ ) as in ship rats ( $n=6$ ). This lack of arboreal prey species is unexpected, because the 'arboreal' lifestyle of *R. rattus* (Harper & Bunbury 2015) could have been expected to lead to greater consumption of arboreal squamata prey by this species. Although the relative abundance of the two rodent species is not identical at our two study sites, their overall skink predation appears to be almost identical. We believe the small differences observed might be explained simply by the foraging behaviour of each rat species. The ship rat is arboreal with a diet mostly made of fruits and plant items (Shiels et al. 2014), on the other hand, the Pacific rat is a ground forager that consumes more invertebrates and fewer plants than the ship rat (Shiels et al. 2013). Our dietary analysis reveals the same pattern and accurately describes the differences in the diet of the two species; for example, feather remains were found in ship rats only, whereas earthworms were more abundant in Pacific rat guts.

We found slightly more squamata remains in *R. exulans* than in *R. rattus* in this study, as Pacific rats are smaller, ground foragers. However, more samples from other habitat types are needed to confirm this difference. Prey size does not seem to vary with the size of the rodent predator. The preyed-upon skinks in our study (42–102 mm) were in the middle of the size range of the species present at these sites (25–200 mm), and the biggest of these species was consumed equally by both rat species. The skink species most frequently consumed are nocturnal, which corresponds to the rodent activity period and could explain the high rates of occurrence of these species in rat diets. Prey species active at night could therefore be more sensitive to rat predation risk than diurnal species, as observed by Towns (1991).

Cumulative impacts have been suggested for sympatric introduced rodents (Montgomery et al. 2012). Here, our observations reveal that the rodent pressure is not homogeneous across the different skink species. We found *Kanakysaurus viviparus* and *Graciliscincus shonae* to be the most consumed skinks ( $\geq 6\%$  of rats) globally and per rodent species, while the others skinks were found in less than 3% of rats. An associated study explored the abundance of each skink species at the two sites using sticky-trap grids (Jourdan et al. 2014). This study revealed that *K. viviparus* was the fourth most abundant species at Tiebaghi and *G. shonae*, a cryptic species living in the litter, has never been caught on sticky traps. This observation may indicate that some skink species are preferentially preyed upon by rodents. This pattern being shared by the two rodents means there could be a cumulative predation pressure upon some skink species. Unfortunately, two of the three most consumed species have threatened conservation status, which reinforces the stakes of this cumulative negative impact on skinks.

Our results confirm predation by introduced rodents to be a potentially important issue for skink conservation in New Caledonia, as some threatened species appear to be regularly

preyed upon. However, this study examined only two sites in forests on ultramafic soil and it would be interesting to investigate introduced rodents' diet in other habitats like primary rainforest, dry forests, littoral habitats and some of the multiple islets surrounding New Caledonia. All these habitats are known to host endemic squamata, among the richest and most endemic of the archipelago's terrestrial fauna (Pascal et al. 2008). Moreover, the lack of ecological information on most of the New Caledonian skink species highlights the need to conduct research in order to better understand the pressures acting upon them. Particular attention needs to be paid to micro-endemic species (short range endemism) with unfavourable conservation status, especially because the three main types of pressures on biodiversity (Pereira et al. 2012) coexist in New Caledonia: (1) habitat destruction and fragmentation induced by mining activities, wildfires and urbanisation; (2) impact of multiple invasive species (rodents, feral cats, ants, etc.); and (3) effects of climate change. As elsewhere in the world, and particularly in tropical islands, addressing the second category of threats is perhaps the most feasible task in the short term. Control of new introductions is essential at points of entry (e.g. airports, harbours), but action can be taken against the species already present, especially in the areas most sensitive to biological invasions. According to Blackburn et al. (2011)'s proposals, rodent impacts could be addressed either by eradication or by mitigation. Rodent eradications have been implemented on several islands, sometimes leading to the recovery of seabirds, invertebrates, plants, forest birds and even lizards (Townes 1991; Smith et al. 2006; Townes et al. 2006; Le Corre et al. 2015; Jones et al. 2016). However rodent eradication appears to fail more often in tropical areas and eradications on human-inhabited islands remain a challenge (Russell & Holmes 2015). Therefore, for the New Caledonian mainland (18 575 km<sup>2</sup>), a complete removal is almost impossible given current rodent control methods. However, control and monitoring of rat populations at particularly sensitive sites can be implemented, so as to limit both population sizes and impacts (Q. Duron pers. comm.). At the Tiebaghi site for example, the rat impact upon *K. viviparus* (En) and *M. taom* (CR) is alarming and may warrant an urgent control program. According to Norbury et al. (2014)'s observations on native skink species recovery in New Zealand, exclusion fences were the most cost-effective option while considering small patches below 1 ha. Considering medium-sized patches from 1 to 219 ha, the same authors highlighted leaky fences as the 'best' solution, whereas lethal trapping appeared most efficient for areas larger than 219 ha, but recent control methods such as A24 self-resetting traps are promising for multi-species control on islands (Carter et al. 2016). As suggested in Doherty and Ritchie (2016), managers must consider the whole range of management approaches, methods, contexts and objectives in order to make control actions the most efficient. For example, in a tropical island hotspot of biodiversity threatened by mining activities, rodent control programs could also be implemented in a biodiversity offsetting perspective as suggested in Holmes et al. (2016). While the support of the population is absolutely essential in human-inhabited contexts (Glen et al. 2013), we believe that it is also fundamental to the conservation of native biodiversity on all islands. As underlined by Pascal et al. (2008), joint involvement is required in New Caledonia if we are to preserve a unique reptilian fauna from growing threats.

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