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Island of opportunity: can New Guinea protect amphibians from a globally emerging pathogen?

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Concepts and Questions

Island of opportunity: can New Guinea protect amphibians from a globally emerging pathogen?

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Running heads:

DS Bower *et al.*

New Guinea frog pathogen

The amphibian chytrid fungus *Batrachochytrium dendrobatidis* (chytrid) has caused the most widespread, disease-induced declines and extinctions in vertebrates recorded to date. The largest climatically suitable landmass that may still be free of this fungus is New Guinea. The island is home to a sizeable proportion of the world's known frog species (an estimated 6%), as well as many additional, yet-to-be-described species. Two decades of research on the chytrid fungus have provided a foundation for improved management of amphibian populations. We call for urgent, unified, international, multidisciplinary action to prepare for the arrival of *B dendrobatidis* in New Guinea, to prevent or slow its spread within the island after it arrives, and to limit its impact upon the island's frog populations. The apparent absence of the fungus in New Guinea offers an opportunity to build capacity in advance for science, disease surveillance, and diagnosis that will have broad relevance both for non-human animal health and for public health.

Front Ecol Environ 2019;

In a nutshell:

- The island of New Guinea is a biodiversity hotspot for amphibians, whose populations are – to the best of our knowledge – currently unaffected by the amphibian chytrid fungus *Batrachochytrium dendrobatidis*
- In preparation for the likely arrival of the fungus and its spread within New Guinea, international and multidisciplinary coordination is urgently required
- To help mitigate pending disease-related impacts and conserve the island's amphibians, we recommend several actions, including prioritizing frog species based on their level of susceptibility, slowing pathogen transmission, and improving our understanding of changes in frog communities

Earth's sixth major mass extinction event has begun and amphibians in particular are in peril; over 40% of amphibian species are threatened with extinction (Stuart *et al.* 2004). The Global Pandemic Lineage of the amphibian chytrid fungus *Batrachochytrium dendrobatidis* (the strain of the fungus that has caused mass die-offs and population declines of amphibians – referred to hereafter as

chytrid) is the foremost example of the impact of an emerging infectious disease on wildlife worldwide, and is responsible for the most widespread, disease-induced declines and extinctions in vertebrates recorded to date (Wake and Vredenburg 2008). Originating from Asia (O’Hanlon *et al.* 2018), chytrid now occurs on every continent inhabited by amphibians (Bower *et al.* 2017a), and the fungus has spread repeatedly to naïve host populations, where it has caused mass mortality, population extirpations, and species extinctions (Berger *et al.* 1998; Lips *et al.* 2006).

New Guinea is the world’s largest tropical island and may be the last major center of amphibian biodiversity free from chytrid (Swei *et al.* 2011; Dahl *et al.* 2012; Bower *et al.* 2017a). The lack of detection of this pathogen in New Guinea is notable because the island is home to approximately 6% of the world’s known frog species, plus many more undescribed species. New Guinea is vulnerable to the introduction of chytrid because of its close proximity to centers in the Asian pet trade, as well as infected sites in both Indonesia and Australia. Rising levels of international commerce and cross-border movement of people elevate the risk of pathogen introduction (Natusch and Lyons 2012), and tourism, logging, petroleum development, and mining increase access to formerly remote localities. Climatic modeling shows that large areas of the central highlands of New Guinea have climates favorable to the fungus (Figure 1; see WebPanel 1 for more detailed methods). Many of the Australian frogs that have declined since the 1970s have close evolutionary and ecological affinities with the New Guinean frog fauna, strongly suggesting that, as in Australia, dramatic declines will occur if the pathogen becomes established on the island. Chytrid cannot be eradicated from large areas and can spread rapidly once it enters a naïve region. Stringent, well-coordinated biosecurity protocols, disease surveillance, and emergency response plans could prevent widespread biodiversity loss in New Guinea resulting from the presence of the chytrid fungus.

Intersection with policy and society

When global amphibian declines were first documented (in the late 1980s), scientists’ understanding of amphibian population dynamics was poor, the responsible agent had not been identified, and little was known about the host–pathogen interactions underlying many population declines. This lack of knowledge resulted in delays in appropriate management and research on imperiled amphibian populations. Two decades of research now provide a basis for improving management strategies for amphibian populations threatened by chytrid. Given the recorded absence of chytrid in New Guinea, preventive strategies are necessary now, although options to manage chytrid-affected areas may be useful post-invasion (Scheele *et al.* 2014b). Knowledge of host–pathogen interactions can inform predictive assessments; researchers can identify the most climatically suitable areas for the fungus

and, on a finer scale, use ecological information to identify high-risk guilds and consequently predict species' responses (Bower *et al.* 2017b). For example, stream-associated frog populations at high elevations are disproportionately affected, further highlighting the vulnerability of New Guinean species, many of which inhabit the island's extensive highlands (Murray and Skerratt 2012). Furthermore, the physiological susceptibility of species can be tested by exposure to standardized densities of zoospores in the laboratory. Improved knowledge of the biology and epidemiology of declines provides an important opportunity to manage the threat to a vulnerable area with high amphibian diversity.

Biodiversity in New Guinea remains poorly documented, hampering accurate estimates of species' losses; moreover, the inconsistent declines experienced globally due to the chytrid pandemic present challenges in predicting which specific taxa in New Guinea are at risk. Even among closely related taxa, some species are susceptible and experience rapid declines, while others are largely unaffected (Scheele *et al.* 2017). This remains an important knowledge gap, one that is complicated by the fact that many non-impacted species can still become infected and act as reservoir hosts (Stockwell *et al.* 2016; Brannelly *et al.* 2017). However, observations of Australian chytrid impacts can be used to infer which species' groups might be more susceptible and estimate numbers of species that might be impacted. The Australian frog fauna has a strong affinity with that of New Guinea, with many closely related species. In Australia, 22% of pelodyadid (19/88), 7% of limnodynastid (3/44), and 19% of myobatrachid (17/88) species have experienced declines or extinctions since the arrival of chytrid. Using this as a guide, then on the Papua New Guinea (PNG) side of New Guinea alone (for which data are available), 22 pelodyadids (n known species in PNG = 102), 1 limnodynastid (n known species = 4), and 1 myobatrachid (n known species = 4) may experience similar declines (Figure 2; Table 1).

It is more difficult to predict impacts on the highly speciose microhylids in PNG ($n = 212$ species) or ranids ($n = 12$ species). There are only a few microhylid species and one ranid species in north Queensland, Australia, which does not mirror the diversity of forms in New Guinea. Microhylid frogs in Australia are represented by just two genera, restricted to the northern fringe of the continent, and they lack the phylogenetic, morphological, and ecological diversity exhibited by this group in New Guinea. Frogs with direct developing embryos – a reproductive mode exhibited by all New Guinean microhylids – experience more rapid increases in chytrid infection loads and higher mortality rates than species with aquatic larvae (tadpoles), such as pelodyadid frogs (Mesquita *et al.* 2017). Although declines related to chytrid infection have not been reported for the small number of Australian microhylids and at least some species appear resistant (Hauselberger and Alford 2012), declines could possibly be similar to those of most other major frog lineages around the globe that

have been exposed to chytrid for which there are data. We therefore conservatively place these groups at an average risk of decline compared to other well-studied frog families in Australia (calculated at ~16%), which could put the number of at-risk species as high as 38 microhylid and two ranid species (Table 1). Extrapolating the number of at-risk species from the various families to the entire island of New Guinea (including both the PNG and Indonesian sides of the island) produces a concerning result: potentially up to 100 or more of the ~500 species in New Guinea are likely at risk, with many more yet-to-be-discovered species also at risk.

The loss of substantial numbers of frog species is likely to have broad ecological effects. Changes to primary production associated with loss of tadpoles and frogs can influence ecosystem structure and function, including changes to nutrient cycling, leaf litter decomposition, and invertebrate populations (Whiles *et al.* 2006, 2013), potentially leading to an overall net loss of biodiversity.

Action is required immediately to prepare for chytrid emergence in New Guinea. To be effective, international collaborations incorporating multiple disciplines need to develop strategies to prevent and slow the spread of chytrid to and within New Guinea (PNG and the Indonesian provinces of Papua and West Papua). Here, we present a five-stage action framework to guide this process (WebFigure 1).

Stage 1: preparedness

A collaborative task force of key partners in science and policy should be formed, in conjunction with international aid, to develop a threat abatement strategy and marshal resources to implement that strategy (WebTable 1). Identifying the most likely points of entry to New Guinea and the avenues by which the pathogen will spread is needed, to help direct resources for monitoring and subsequently abatement. It is also critical to formulate an emergency response plan to chytrid, and to prepare in advance any approvals and other foundations (eg landowner approval and community consultation) required for its rapid implementation. Risk assessments associated with the importation of freshwater products and equipment need to be incorporated into future policies and regulations, given the expected damaging consequences of chytrid's introduction into New Guinea. Management and research need to occur in concert with policy development that includes consultation with landowners and increases the capacity of communities to respond to the arrival of the fungus. Timely action will likely rely on developing partnerships with organizations already working in New Guinea that have established research and community programs.

Stage 2: prevention

Reducing the probability of introduction can be achieved through a combination of strategic actions, such as enforcing quarantine measures through policy changes, investing in compliance, promoting education, and minimizing risks, including transportation of infected sources (eg frog legs, fish, equipment). Imminent introduction of pathogens has been averted in several locations through lobbying governmental representatives to amend legislation to reflect newly identified threats, implementing voluntary import and movement bans by hobby groups and industry partners, encouraging increased compliance through social media campaigns, and ensuring improved capacity of quarantine stations (WebTable 1).

Stage 3: detection

An island-wide disease surveillance program is required, and must include an amphibian biodiversity survey and long-term monitoring sites that are established along the likely pathways along which the fungus will spread. Such programs have been successful at recording the arrival of chytrid and other pathogens in Madagascar (WebTable 1). Community surveillance for disease outbreaks has been an efficient component for tracking pathogen spread in other systems (eg West Nile virus in crows [*Corvus* spp]), but requires education and recruitment. Research is needed to identify sites of high biodiversity value and to assess additional threats, including those that may act synergistically with the fungus (eg habitat conversion).

Stage 4: response

When the pathogen arrives, predetermined and context-specific management actions should be implemented to minimize disease impact (WebTable 1). No known measures can completely eradicate chytrid from large areas and current options therefore vary in their value (Bosch *et al.* 2015). Reducing the chytrid load in the wild can be achieved on a small scale through habitat manipulation (Roznik *et al.* 2015; Clulow *et al.* 2018) or environmental disinfection, but these actions may have consequences for other species (Woodhams *et al.* 2011; Scheele *et al.* 2014b). Scientists' ability to increase the resistance of hosts is still at an early stage (McMahon *et al.* 2014) and conserving individuals in threatened populations may be the only short-term option for some species (eg captive breeding, gene banking) (Skerratt *et al.* 2016). Identifying and protecting small remnant populations, such as those outside the optimum habitat for chytrid, has been a critical component in preventing extinctions in Australia. Translocation to such habitats also has potential (Germano *et al.* 2015). Creation of disease-free exclosures has also been successful; such exclosures are more cost effective than captive breeding programs and avoid some of the problems (eg behavioral modifications) associated with raising individuals that are destined for reintroduction

under captive conditions (Skerratt *et al.* 2016). Funding to enable these actions is required immediately. Engagement with and assistance from international organizations that garner and administer funds, and that provide resources not yet present in New Guinea, will facilitate the success of these initiatives. International assistance is imperative to ensure positive outcomes and to enhance the current national capacity for conservation action (Laurance *et al.* 2012; Woodhams *et al.* 2018).

Stage 5: recovery

Current initiatives aimed at recovery have had limited success, and are mainly restricted to the ongoing release of individuals from captive colonies and managing specific populations and associated habitats (WebTable 1). Technology is emerging that may provide options for permanent recovery with the implementation of gene banking and translocation of disease-resistant animals but these actions require investment and proof of concept (Kouba *et al.* 2013). There is evidence that some populations afflicted by disease-related declines can recover over time, often through recruitment from nearby persisting populations (Scheele *et al.* 2014a; McKnight *et al.* 2017; Voyles *et al.* 2018). Actions aimed at rescuing individuals during the initial disease epidemic may therefore save species (Scheele *et al.* 2014b). Management strategies can be simple, such as manipulating species or habitats to slow or reduce growth of the fungus (eg applying skin probiotics, translocating species, decreasing canopy cover; Scheele *et al.* 2014b). Effective safeguarding of populations requires action before chytrid arrives in New Guinea, such as establishing and understanding captive breeding of frog species, and gene banking a representative sample to preserve and store genetic diversity (Clulow and Clulow 2016).

Following this five-stage action framework is advisable from an economic perspective, when considering the relative costs and benefits of staged preparation versus emergency conservation efforts. Accurate economic analyses are difficult to achieve because it is difficult not only to equate a financial value to biodiversity but also to predict species' responses under comparative scenarios. However, research and conservation become expensive and more challenging when species are rare (Joseph *et al.* 2009). Initiating work before species decline enables research to commence at much lower costs, because accessing species is much easier logistically and less risky, and answers can be obtained with less effort. The benefit of early action is exemplified in the following comparison between establishing captive breeding protocols for two closely related species of barred frog in Australia (*Mixophyes balbus* and *Mixophyes fasciolatus*), one of which was common at the time of conservation while the other was a threatened species (WebTable 2). The common species required less effort to locate and source, was subject to fewer regulatory requirements and barriers, and was

managed with considerably less time and expense overall.

Not all actions are equally costly and some have more advantages than others. For example, improving biosecurity prevents the import of exotic pathogens, which (if effective) is cheaper than the costs required to conserve populations after declines have begun (eg disease exclusions). In addition, while captive breeding is critical for the persistence of some threatened species, gene banking can provide a less expensive and more extensive reserve of genetic material, although success depends on preemptive planning and experimentation.

Further documentation of New Guinea amphibians is an immediate priority to better understand patterns of existing diversity. Understanding community composition prior to pathogen invasion will enable scientists to detect the pathogen's impacts, and therefore biodiversity surveys should be conducted in tandem with disease surveillance. Surveys and surveillance are important for understanding causes of introduction and spread, and for successful application of context-specific management actions. Documenting the ecosystem-scale effects of an introduced pathogen over time requires an understanding of system function before and after invasion; areas that are currently chytrid-free represent important opportunities to examine baseline conditions. How systems are changed by the emergence of chytridiomycosis is currently poorly understood due to the scarcity of matched pre- and post-invasion datasets. Disease surveillance also provides opportunities to build the capacity of working groups in the region (eg training individuals to become familiar with threatening processes) and to mount a coordinated management response to the threat. A preemptive national monitoring plan with coordinated disease surveillance in Madagascar (Weldon *et al.* 2013) has provided scientists with the ability to respond to the threat posed by the fungus. Similar responses are being developed for mitigating the introduction and impacts of the recently discovered salamander chytrid *Batrachochytrium salamandrivorans* (Bsal) in the US (Grant *et al.* 2017).

National differences in policy between PNG and Indonesia increase the complexity of biosecurity programs, and pathways of disease introduction will vary between the two countries. However, the situation provides opportunities for both countries to collaborate and contribute toward advancing science and conservation in New Guinea; the Indonesian provinces of West Papua and Papua and the country of PNG are hugely underrepresented in scientific research (Wilson *et al.* 2016). Conservation and research in New Guinea is complicated by local-scale social and economic factors. Establishing protected areas and conducting research and natural resource management on traditional lands are dependent on close collaboration with local communities. In both PNG and Indonesia, any on-the-ground conservation action must be approved at the national, provincial, and local community levels. Most critically, customary landowners – indigenous communities who own the majority of land in New Guinea (~85% in PNG; Filer 2012) – must be involved in the programs

and empowered to lead them, if success is to be achieved. The most efficient way to do this will be to engage with and foster the growth of established organizations that have working relationships with landowners throughout the island.

Opportunities for capacity building

In New Guinea, the apparent absence of chytrid provides an opportunity to build capacity for science, disease surveillance, and diagnosis that will have broad relevance for human and animal health. Coordinated monitoring should involve existing international partnerships that support natural resource management, including initiatives for land managers and local students from New Guinea. For example, the well-established skill-sharing partnership between the Port Moresby Nature Park in PNG and Zoos Victoria in Australia is an ideal platform from which to develop captive management and research capabilities in the PNG community. Similarly, ecotourism may provide an opportunity for education through employment and training of local staff. Collaboration with community-based conservation, and research organizations in New Guinea that have preexisting study sites (eg YUS Conservation Area in Morobe Province, Mt Wilhelm altitudinal transect site, Wanang in Madang Province), will also be essential because successful engagement of landowners requires time to build trust and cultural understanding. In addition, the establishment of long-term monitoring sites for amphibian disease surveillance could serve as a social benefit by directing funds into capacity building through training and by providing a long-term source of income for communities that preserve their land. It also offers a chance to increase the resources available to in-country museum and data repositories, and to ensure that data are openly accessible, and that education is part of the scientific process. Possible sources of logistical and financial support include international non-governmental organizations, government agencies, and industries operating inside New Guinea with an interest in improving animal health and maintaining biodiversity.

Documenting the island's amphibian biodiversity is critical for the development of the proactive, innovative, and experimental conservation measures that will be necessary should population declines begin (Figure 3). In summary, given the likelihood of chytrid's eventual arrival to New Guinea, we recommend prioritizing the conservation of the island's frog species based on their relative imperilment, quantifying changes in frog communities to better understand and mitigate the pathogen's potential impacts, promoting biosecurity and education to reduce the transmission and spread of the pathogen once it arrives, and ultimately rescuing frog populations and thereby preserving amphibian biodiversity. Achieving this requires funding, planning, and coordinated efforts by a dedicated task force, as well as the implementation of an active management plan, similar to the framework proposed here. Our call to action is urgent.

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Supporting Information

Additional, web-only material may be found in the online version of this article at

Figure captions

Figure 1. Areas of climatic suitability for the amphibian chytrid fungus (*Batrachochytrium dendrobatidis*) in New Guinea. The central highlands (in red) provide optimal habitat for the fungus, and increased accessibility to these remote areas has raised the risk of its introduction. See WebPanel 1 for more detailed methods.

Figure 2. Relative threat of chytrid invasion to different frog families in Papua New Guinea (PNG), projected from the proportion of frog species in each family that declined or became extinct due to *B dendrobatidis* in Australia (based on Skerratt *et al.* [2016]). For families where little or no data are available (ie Microhylidae, Ceratobatrachidae, Ranidae, and Dicoglossidae; indicated by the

question marks in the figure), we used the mean declines observed from the other families as a proxy. Values in panels (a) and (b) are provided for PNG and are therefore expected to be higher for the island of New Guinea overall. From a conservation management perspective, species' groups of greatest concern can be considered in two different ways: (a) groups containing a greater number of at-risk species are of highest concern, while groups containing fewer at-risk species are of less concern; and (b) groups containing small numbers of species that are at a higher risk of being affected represent a greater proportion of unique diversity, whereas groups containing large numbers of species have a greater number of similar species and are collectively of less concern. Red and green indicate areas of greatest and least threat, respectively.

Figure 3. An illustration of frog diversity in New Guinea. (a) *Sphenophryne cornuta* with young, (b) *Lechriodus aganoposis*, (c) *Oreophryne oviprotector*, and (d) *Callulops doriae*.

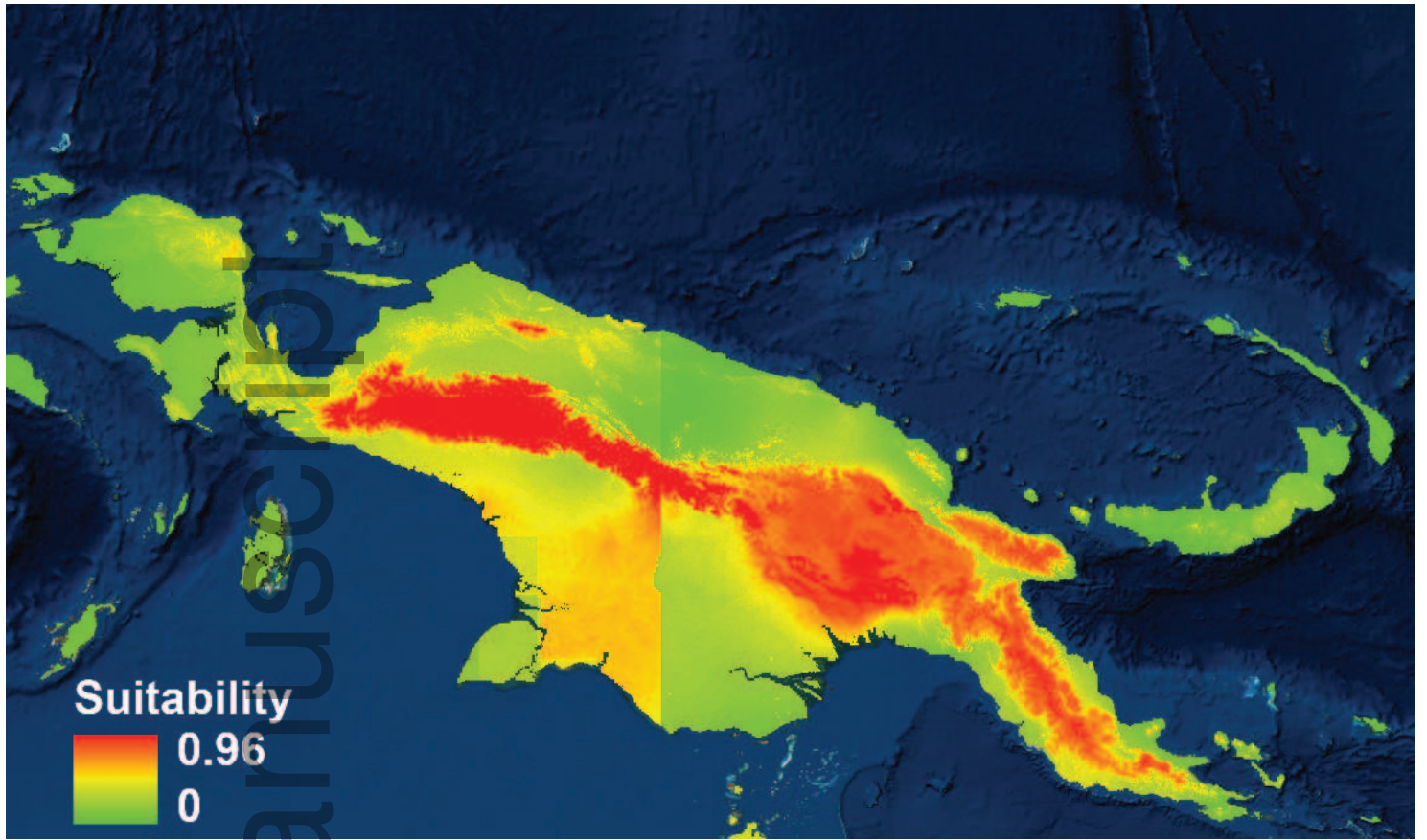
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Table 1. Projected declines of frogs in Papua New Guinea (PNG) based upon declines observed in Australia

Family	Number of species in Australia	Percent declined in Australia	Number of species in PNG	Predicted decline (number of species) in PNG
Ceratobatrachidae	0	–	44	8*
Dicroglossidae	0	–	2	1*
Limnodynastidae	44	7	4	1
Microhylidae	24	0*	212	38*
Myobatrachidae	88	19	4	1
Pelodyadidae	88	22	102	22
Ranidae	1	0*	12	2
<i>Total</i>	<i>245</i>	<i>Mean = 16</i>	<i>380</i>	<i>73</i>

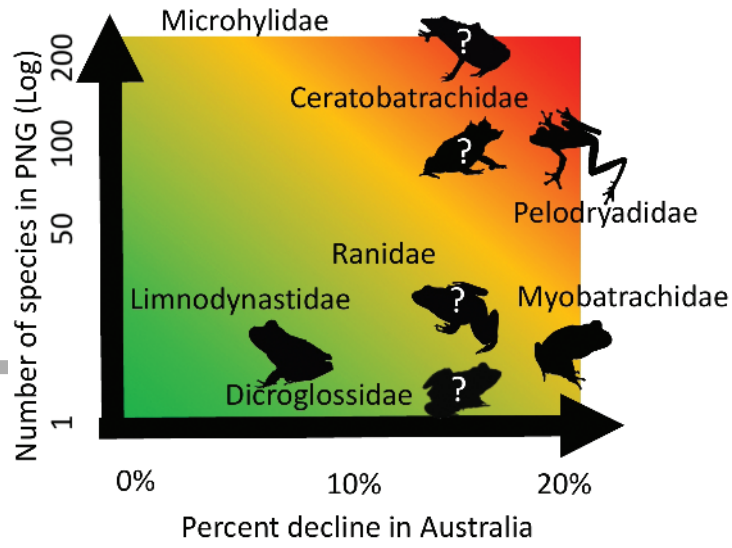
Notes: Asterisks indicate where predictions for a certain family are based upon a mean decline of 16% calculated from the three main families in Australia collectively, due to there being insufficient data, too few species, or no species at all in Australia to draw robust conclusions.

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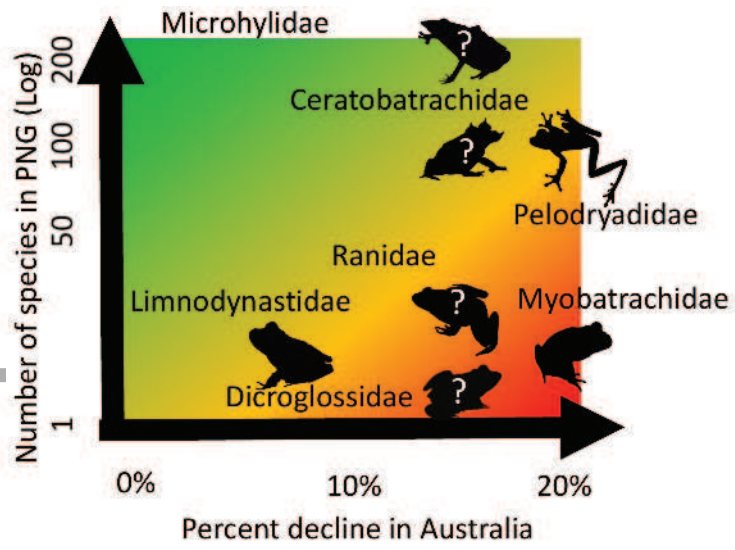


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