

Article

The Demise of the Golden Toad and the Creation of a Climate Change Icon Species

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Abstract

There is an unavoidable degree of uncertainty associated with future climate projections, and even more unpredictability about the potential impact of different climate scenarios on the ecology and distribution of organisms. Conservationists face a major public communications challenge to both raise awareness and mobilise support for conservation and climate change mitigation/adaptation policies while realistically representing complex and uncertain scientific information. Here, we illustrate the interplay of these competing communication goals through a review of the representations of the golden toad in the print media and peer-reviewed literature (in English and Spanish). Since its disappearance in 1989 the toad has become an important conservation flagship species that has been frequently portrayed as the first verified extinction attributable to global warming. Moreover, there was an increase in the certainty of published news items regarding the toad and its demise, especially in the late 1990s. The uncertainty surrounding the toad's disappearance (apparent in the primary research literature) was poorly represented in the popular press. The transformation of the toad into an iconic species for climate change advocacy may reflect a perceived need to supply tangible evidence of biodiversity consequences arising from climate change and highlights the challenges facing conservation scientists in communicating scientific concerns and uncertainty via the media.

Keywords: amphibian decline, climate change, *Bufo periglenes*, conservation, *Incilius periglenes*, media representation, uncertainty

INTRODUCTION

“Perhaps the most common outcome of the scientific process is not facts, but uncertainty” Friedman et al. (1999: vii)

“For many, false prophecy is still less frightening than uncertainty” Reading (2004: 15)

Global concern about the conservation status of amphibians began to gather momentum at the first World Conference of

Herpetology in 1989 (Sarkar 1996). Numerous scientists at this meeting argued that there was a general declining trend among amphibian populations in different parts of the world, but with no obvious single cause (Blaustein and Wake 1990; Blaustein 1994; Houlahan et al. 2000). Several hypotheses were suggested, such as ultraviolet radiation, pesticides, introduction of alien species, toxicants, deforestation, and pathogens (reviewed in Blaustein et al. 1998; Collins and Storfer 2003; Cushman 2006; see Appendix 1). These threats are not mutually exclusive and some have proved difficult to identify definitively or separate in the field (Collins and Storfer 2003), possibly because sub-population decline is inevitable in metapopulation with high demographic variability—a characteristic of many amphibian populations (Alford and Richards 1999; Gillespie 2010).

The golden toad, *Incilius (Bufo) periglenes* (Savage 1966), is a classic example of a species for which the causes

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of decline and eventual extinction are poorly understood, but which nevertheless has become an important species within climate change discourse. The golden toad was first discovered in the cloud forest of the Monteverde region of Costa Rica in 1964 (Savage 1966). The small population size and extremely localised geographic distribution meant that the toad was always a conservation concern and, in 1972, a small reserve of less than 4 sq. km was established that encompassed the entire known global population (Crump et al. 1992). Subsequently the reserve was expanded to encompass around 105 sq. km.

Although the golden toad was difficult to survey accurately within the dense undergrowth of the cloud forest, accurate counts could be made for a few weeks in April when individuals emerged from the forest to mate in temporary pools (Crump et al. 1992). Thus, unlike the vast majority of extinctions (*cf* Ladle 2009), the final, rapid disappearance of the golden toad was well documented. More than 1,500 toads were observed in 1987, but only a single toad was observed at the main known breeding site in 1988 and 1989 while seven adult males and two adult females were recorded 4–5 km away in 1988. No verified sightings have been reported since (Crump et al. 1992; Pounds and Crump 1994; Sarkar 1996). However, published accounts of the procedures used to survey and monitor amphibians in the Monteverde cloud forest reserve are limited and rather imprecise. Pounds et al. (1997: 1316) write that the “Monteverde reserve has been *almost constantly* patrolled for 25 years,” a comment that Wake and Vredenburg (2008) cited as “daily monitoring.” To our knowledge, there is no published account (in print or online) on the frequency of toad monitoring, the extent of the monitored area after 1990, the proportion of the research area that has been systematically sampled, sampling method (day or night samplings), or whether any other forests in the vicinity have been searched. This apparent lack of systematic sampling of the reserve and/or of the wider region introduces a degree of uncertainty into data on the rate and timing of the observed decline (Crump et al. 1992; Sarkar 1996).

Initially, the toad’s disappearance was linked to the severe neotropical droughts of 1987–1988 attributed to El Niño-Southern Oscillation (ENSO) conditions (Crump et al. 1992; Pounds and Crump 1994). However, shortly after the toad’s disappearance, Crump et al. (1992) acknowledged that other factors (e.g., non-specific pathogen attacks) might have played a role in the extinction and also commented that impacts of prior environmental degradation (initiated before monitoring work began) could not entirely be ruled out. The articles based on population monitoring leading up to the crash made no mention of disease playing a role in the toad’s decline. Indeed, Crump et al. (1992) commented that data to address this possibility were lacking. Pounds et al. (1999) subsequently published a high-profile article in *Nature* arguing that climate change was probably responsible for the decline or disappearance of a number of species of birds, reptiles, and amphibians in the area, citing the golden toad as a specific example. Pounds et al. (2006) provided

additional climate-trend analyses and developed a more refined argument for the toad’s extinction based on the temperature-sensitivity of the behaviour of the pathogenic chytrid fungus *Batrachochytrium dendrobatidis* (but see Lips et al. 2008; Rohr et al. 2008; Cheng et al. 2011; Garner et al. 2011, for counterarguments against this hypothesis). Pounds et al. stated that their data supported with “very high confidence” the case for large-scale climate warming being key to the loss of a number of amphibians and implicated this temperature-sensitive chytrid as an integral component of the causal nexus leading to amphibian declines. They focused on species in the genus *Atelopus* (harlequin frogs) for the most part, but also cited the golden toad as subject to the same drivers (Pounds et al. 2006). Significantly, these later arguments did not cite any new evidence regarding the extinction of the golden toad.

To attribute climate change as the single major cause of any extinction event is problematic (Whitfield et al. 2007; Ladle 2009) because there is often no proper way of scientifically distinguishing a specific climate-change influence from historical variability in climate and other environmental conditions (Anchukaitis and Evans 2010). The arguments of Pounds et al. (1999, 2006) that climate change was the main causal factor in the extinction of the golden toad coincided with a marked increase in climate change discourse in conservation generally. This followed a shift from 1987 to 1992 in the United Nation’s focus from “poverty reduction in developed countries” to the “biodiversity crisis,” including climate change, biodiversity, and forests (McManus 2000). Climate change was one of the main issues during the United Nations Conference on Environment and Development (UNCED) in Rio 1992, the Conference of the Parties in Geneva 1996 (COP2), and Kyoto 1997 (COP3).

More generally, the focus of the international community on climate change has had significant consequences for conservation (Jepson and Ladle 2010), not least because many sources of conservation research funding have become linked to understandable concerns about how changing climate might impact wildlife and ecosystems. Many conservationists and conservation organisations quickly aligned behind this increasingly dominant environmental theme (Ladle et al. 2005; Ladle and Jepson 2010). In this context, the transformation of the golden toad from an obscure species of mainly herpetological interest into a prominently cited example of a contemporary extinction event (e.g., Pearson 2011) and a global icon for climate change (Stork and Samways 1995) provides an intriguing window into the use of scientific information for conservation advocacy.

To better understand the demise of the golden toad and how its story has been used and relayed, we present a comparative assessment of the reporting of its extinction in the academic literature (peer-reviewed journal articles) and in the news media (internet and newspapers). We also reflect on the potential implications for public perceptions of science and conservation.

MATERIALS AND METHODS

We searched the peer-reviewed journal literature via two databases: Scopus and the ISI Web of Knowledge. We obtained six results from Scopus that included “*Bufo periglenes*” (title, keywords, and body), and six that included “golden toad.” From the ISI Web of Knowledge, we obtained 18 articles that included the term “*Bufo periglenes*” and 29 that included “golden toad” (Appendix 2). We did not find any peer-reviewed article that included “*Incilius periglenes*.” In total, we retrieved 40 peer-reviewed articles published between 1972 and 2010.

We used the LexisNexis® database to search all news articles from all available sources of published information (newspapers, newswires, magazines, broadcast transcripts, and some blogs) that contained the words “golden toad” and “*sapo dorado*” (common name in Spanish). This search included articles published and captured electronically from January 1983 to March 2010. In all, we obtained 530 articles published in Spanish and English. After screening and deleting duplicated news or reports not related to amphibians (such as cultural or sports news), we compiled a database of 400 articles.

We recorded the following information for peer-reviewed and news articles: title/headline, month, year, type of article/news, name of the source, country of release, and whether the author(s) mentioned other amphibian species or other species in general. We categorised presumed causes of disappearance for *I. periglenes* or population changes for other specifically mentioned amphibian species as: climate change, habitat loss (including deforestation), pollution (including pesticides, chemical wastes), ultraviolet radiation, alien species, acid rain, ENSO (i.e., climate variability as opposed to long-term change), and diseases (including viruses and fungi). If the identified cause of population change did not fit into

the above classification, we recorded it as “other causes” and recorded any additional information on population status (decline, disappearance, extinction, etc.) mentioned in the article.

To further identify and characterise reports in media sources and academic journals we searched for signifier keywords or statements in the headline or in the main body of the text such as: wiped out, extinct(ion), probably or believed to be extinct, not seen, endangered, threatened, disappeared, vanish(ed), declining, killed (fatal), mass extinction and “canaries in a coal mine.” We also recorded other information contained in media reports such as direct quotes attributed to non-governmental organisations (NGOs), university researchers, and government officials, as well as events such as conferences, and scientific articles related to the published news. Additionally, we surveyed 92 peer-reviewed articles (selected haphazardly from 385 papers identified via Scopus in January 2011), which cited Pounds et al. (2006), to specifically assess how authors represented this important article in the scientific literature. To avoid operator variance the first author performed all literature research, data extraction, and compilation to standardise interpretation and classification of the information.

RESULTS

News items containing the term “golden toad” increased irregularly over time with four peaks in frequency (Figure 1) and an annual mean of 14.86 ± 15.39 . In contrast, the number of peer-reviewed articles in scientific journals containing either “golden toad” or “*Bufo periglenes*” or “*B. periglenes*” was consistently low over the study period, with a mean of 1.33 ± 1.33 articles per annum. The frequencies of news items and peer-reviewed articles were not correlated (adjusted $R^2 = 0.002$, $P = 0.31$, Figure 1).

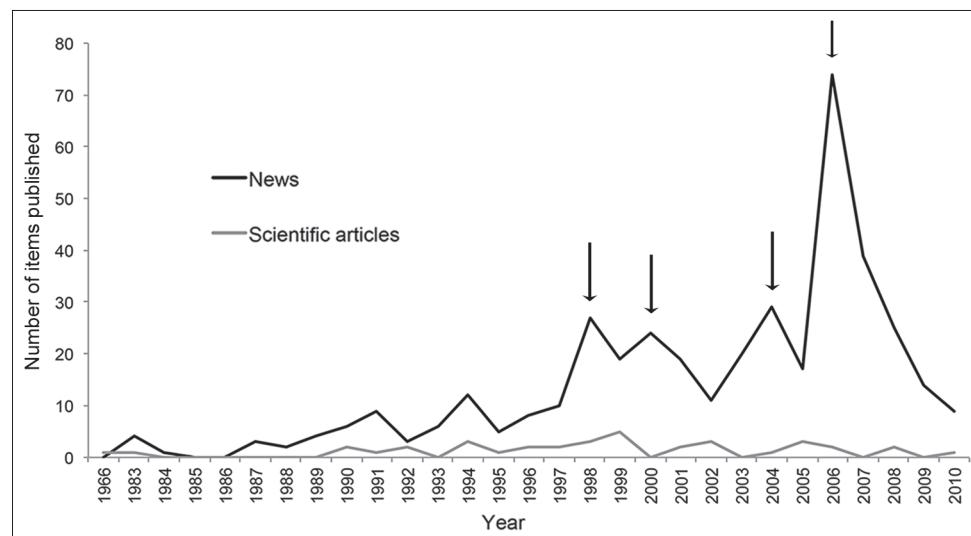


Figure 1
Number of peer-reviewed articles (sources: ISI Web of Knowledge and Scopus) and news (via LexisNexis®) published containing the term “golden toad” and/or “*Bufo periglenes*”.

The description of the golden toad was in 1966, following which we could not find peer-reviewed articles until 1983.

The first news in the LexisNexis® database occurred in the same year.

Authors of popular articles invoked different causes for the disappearance of *I. periglenes* from Monteverde through time. Several causes were identified shortly after the extinction event was reported; those causes typically were described as having high uncertainty. This changed over time and climate change and the amphibian fungal disease, chytridiomycosis, became the dominant reported causes by 2000 (Figure 2). As the number of articles varied through time, we used the proportion of the number of times that different causes were mentioned within the news to illustrate these trends (Figure 2). It should be noted that some of the articles discuss other amphibians in addition to *I. periglenes*.

We found it more difficult to quantify any trends in statements regarding causes of declines in the peer-reviewed articles due to the low number of published articles containing the search terms (Appendix 2). From the 40 peer-reviewed articles retrieved from the search, we were only able to use 32 in the analysis. One article provided only a description of the toad, three others were specifically related to life history, and we were unable to obtain copies of another four. Most remaining articles evaluated more than one cause. A large proportion (17) of the peer-reviewed articles highlighted the golden toad as an example of unexplained decline, another seven mentioned weather variability including ENSO, another five chytridiomycosis, and one the pet trade. Six articles mentioned climate change as the main factor driving the extinction (Appendix 2). The change in the strength of the rhetoric used by the news media to tell the story of the golden toad is also reflected in the increase in value-laden adjectives such as "wiped out" or "vanished", which peaked in 2006 (Figure 3). The use of the phrase "mass extinction" in the news media also peaked that year.

Whilst a relatively small number of peer-reviewed articles have been published about the golden toad, some have had considerable impact throughout the popular and scientific media, most notably, the article by Pounds et al. (2006). This article has been cited for various reasons. Forty-eight articles cited Pounds et al. (2006) as an example of disease impacts promoted by climate change or by climatic or environmental variability. Twenty-one articles cited it as an example of species vulnerability to climate change *per se*, while six other articles referred to it as an example of chytridiomycosis, and nine challenged the hypothesis presented by Pounds et al. (2006). Finally, eight articles cited the paper as illustrating other causes of amphibian declines (Appendix 3).

DISCUSSION

The observed change in the public media's descriptions of potential causes of the golden toad's extinction and of the uncertainty associated with them could have been influenced by the way climate change has come to dominate discussions of global change (Liu et al. 2011). Authors of articles in the public media arguably reflected some of the tone of high-profile scientific articles and their associated press releases, such as Thomas et al. (2004) and Pounds et al. (2006). As commented on elsewhere, the former article was widely misrepresented in the news media, partly due to misunderstanding of the uncertainties involved in complex modelling studies and partly as a result of extrapolations contained in the associated press release (Ladle et al. 2004, 2005).

The four recent peaks in the frequency of popular news items about the golden toad (Figure 1) roughly coincide with particular

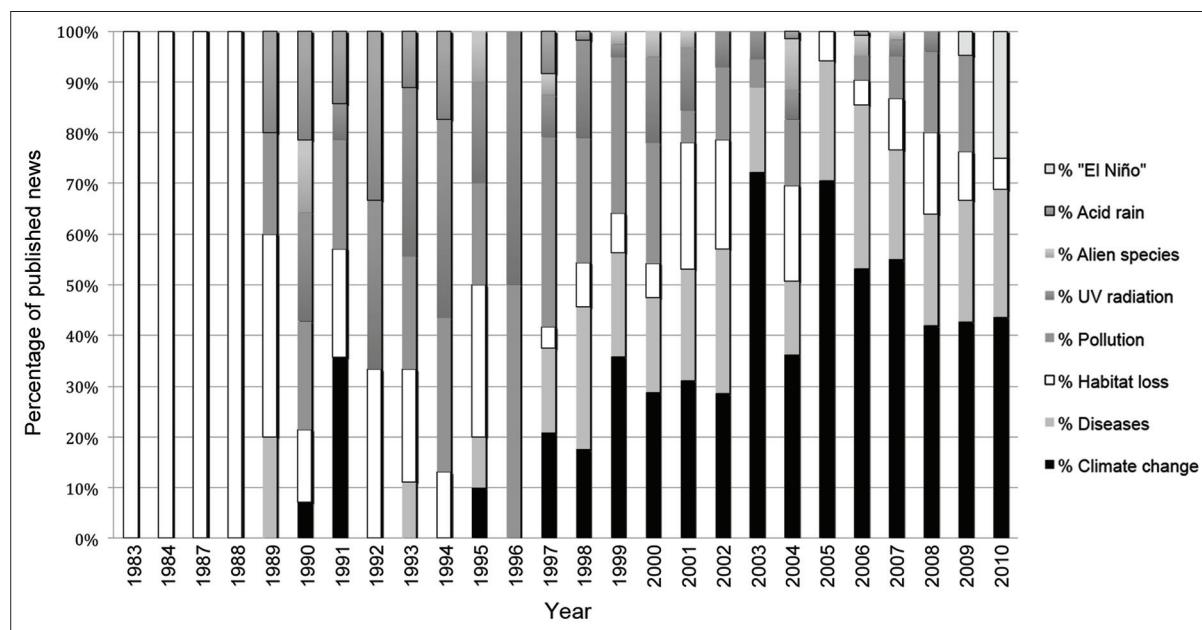


Figure 2

*Proportional number of times per annum that each of the possible causes of amphibian decline were mentioned in news that included the golden toad.
Not all the causes are necessarily related to the disappearance of the golden toad.*

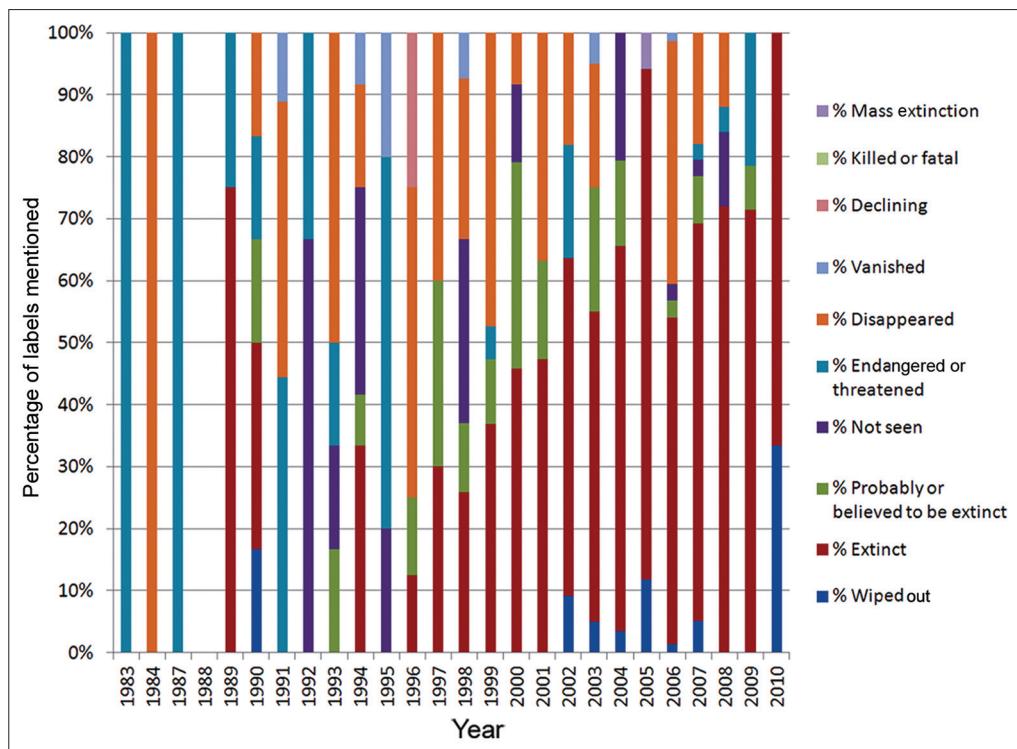


Figure 3
Frequency of use of different labels referring to the disappearance of the golden toad in news items

media events or publications. The first peak coincided with the Kyoto conference in December 1997; the second peak (2000) is contemporaneous with two separate events: the press releases of the WWF report *Living planet* and the publication in *Nature* of the article *Quantitative evidence for global amphibian population declines* by Houlahan et al. (2000). The third peak coincided with two high-profile publications: one in *Nature*, by Thomas et al. (2004) titled *Extinction risk from climate change*, and the other in *Science*, by Stuart et al. (2004) titled *Status and trends of amphibian declines and worldwide extinctions*; and with the release of the IUCN Global Amphibian Assessment (GAA) (IUCN 2008). The final peak, and by far the biggest in terms of the frequency of news items, occurred after the publication of the article in *Nature* entitled *Widespread amphibian extinctions from epidemic disease driven by global warming*, by Pounds et al. (2006).

Although high-profile academic articles may generate news stories, we found no quantitative association between the frequencies of the news-media items we surveyed and that of peer-reviewed published articles about the golden toad. This is not surprising given that the global news media does not typically consider peer-reviewed articles newsworthy by themselves, especially those in less prominent journals. Moreover, the publication of peer-reviewed articles is dictated by factors not necessarily in step with the public media's focus at any given time.

Like the Thomas et al. (2004) study, the Pounds et al. (2006) article is a complex modelling study published in a high-profile journal that suggested more certainty to some readers than often is stated in scientific articles. For example, the authors

stated in the opening paragraph (which served as an executive summary): "we conclude with 'very high confidence' (>99%, following the Intergovernmental Panel on Climate Change, IPCC) that large-scale warming is a key factor in the disappearances [of 67% of 110 species of harlequin frogs and the golden toad]." They concluded the abstract with the non sequitur that "the urgency of reducing greenhouse-gas concentrations is now undeniable." Language such as 'very high confidence' and 'undeniable' conveys technical meaning while also providing strong words for global news stories in the popular media. While the phrase 'very high confidence' still denotes uncertainty, it indicates a very small measure of doubt, unlikely to produce concerns in the minds of the lay reader. Indeed, considering that the chain of argumentation in the paper relies on several untestable assumptions (given the lack of direct monitoring or other autoecological data and thus the poor resolution of what drove the population declines), the use of such a strong expression of confidence appears unwarranted, and indicative of an effort to downplay uncertainty. The use of such a phrase can have consequences similar to those arising from the use of another technical expression common in bioclimatic envelope modelling—'committed to extinction' (e.g., Thomas et al. 2004), which means en route to eventual extinction if no mitigation is undertaken, but which frequently has been simplified to 'will be extinct by date x' by the global news media (Ladle et al. 2005; Ladle and Jepson 2010).

It is hard to determine why it is that particular over-simplified narratives encapsulated by statements such as... "golden toad driven to extinction by climate change"

or “one million species extinct by 2050” gain traction via the media and conservation NGOs, when other explanations or narratives published in similarly respectable or highly cited journals do not (but see for e.g., Ladle et al. 2005). For instance, following the Pounds et al. (2006) paper, the golden toad became a major element of the story in the media, despite the main focus of the article being on a completely different genus, *Atelopus*. Although the golden toad is mentioned in the abstract alongside *Atelopus*, the article provides little further mention (and no new data) of the demise of the golden toad. In contrast, a recent article arguing that the extinction of the golden toad was caused by increased climate variability rather than directional climate change (Anchukaitis and Evans 2010) was not reported widely in public media, despite also being published in a high-profile journal.

The elevation of the golden toad to iconic status illustrates how selected writings in scientific journals and the popular media are related and interpreted, despite scientific uncertainties or improved information over time. The biggest NGOs were quick to use the rhetorical potential of the golden toad and have been instrumental in turning the toad into a flagship species for climate change (see Ladle and Jepson 2010). Stork and Samways (1995) defined flagship species as “popular charismatic species that serve as symbols and rallying points to stimulate conservation awareness and action.” The important status of the golden toad is illustrated clearly by the following quotes from the websites of big NGOs and newspapers: conservation International’s website stated “For Ticos, as Costa Rican natives are known, reducing greenhouse gas emissions and stabilizing the climate is personally important, as the extinction of their emblematic golden toad (*Bufo [Incilius] periglenes*) due to climate change and altered weather patterns is still fresh” (Conservation International 2011); Mr Andrew Kerr of the World Wildlife Fund stated “Global warming has already claimed its first species, with Costa Rica’s golden toad believed to have become extinct” (The Herald 2000); and The Independent (London), on September 18, 2006, stated “Human-induced climate change has already claimed its first victims. The golden toad and the harlequin frog of Costa Rica have disappeared as a direct result of global warming” (The Independent 2006).

Conservation NGOs play an important role in determining conservation agendas, funding initiatives and interventions, liaising with politicians and policy makers, and, significantly, communicating with the public (Jepson and Ladle 2010). However, information reported in scientific journals and further reported and possibly transformed in the public media can become asymmetrical, not necessarily tethered to scientifically recognised realities of uncertainty or improved analyses, and can take on a life of its own, even among relatively informed groups. More generally, our results provide insights into how reports in the peer-reviewed literature and the popular press can be closely related when peer-reviewed articles contain sensationalist or strident

headlines and poorly related when not. The results also show how information from both sources changed over time and suggest ways excerpts of scientific information, once established in the public media, can be used further in important environmental, social, and political contexts around the world.

Nearly two decades ago Pechmann and Wilbur (1994) argued that there was insufficient information about amphibian populations to confirm the perceived worldwide decline of amphibian populations. More recently Salvidio (2009) re-analysed 16 amphibian populations monitored for more than 15 years, and reported that all of them have shown stable long-term population dynamics. This finding is intriguing, although we emphasise that 16 species and 15 years are insufficient sample sizes on a global scale for us to draw any clear conclusions. We see no reason to doubt that amphibians are a threatened taxonomic group as a whole, with many species in danger of extinction due to a range of environmental factors, including climate change (Collins and Storfer 2003; Wake and Vredenburg 2008).

When Pechmann and Wilbur (1994) raised the question of “Playing it safe or crying frog?”, they were alluding to the potential negative repercussions of any incorrect reports of amphibian declines. Almost 20 years have passed since widespread amphibian declines were first reported and population declines have been reported among many species, as they have for other taxonomic groups (e.g., Malcolm et al. 2006; Saino et al. 2011). Today, amphibians are no longer a forgotten group. Initiatives such as the Declining Amphibians Population Task Force (DAPTF) and others have increased general awareness and knowledge about amphibians substantially, although it remains the case that there is a lack of standardised monitoring data for most amphibian species/populations (e.g., Frías-Alvarez et al. 2010).

Communicating science via the popular media is difficult, yet critically important. As some authors have already emphasised, scientists, as sources in the media, have to think carefully about how the information they are giving is going to be interpreted (Friedman et al. 1999). The dynamics and goals of reporting information in the popular media often differ substantially from those of reporting research results in scientific journals (Schmidt 2009). This suggests that as a profession we need to strive harder yet to maintain the integrity of science in the public eye by stating clearly what we know and do not know when writing for a journal or communicating more directly with the public. Whilst scientists cannot control how the information they supply will be represented in the media and by interest groups and the polity, the following steps may reduce the probability of misrepresentation: careful drafting of press releases and responses to questions from the media; avoiding providing potentially misleading extrapolations or ‘sound bites’; and providing succinct summaries of their articles written in layman’s terms which are published on institutional websites as soon as media coverage is initiated. These summaries should include clear

statements of the key assumptions and caveats of the research, the funding sources, and any conflicts of interest. We also recommend full use of digital communication platforms such as blogs (Ashlin and Ladle 2006) and social networking sites and that authors work closely with institutional press offices and take opportunities to participate in media training workshops and courses.

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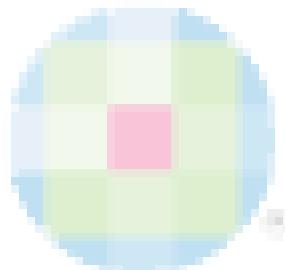
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Appendix 1

Some examples of causes linked to amphibian populations declining around the world. Between parentheses are the numbers of articles found related to the topic at the moment of the search. The threats are divided into major groups (underlined), and divided further as finer processes.

Threat type	Proposed mechanism	Consequences or change in status (examples)
<u>Habitat loss</u>		
Habitat transformation (18)	Amphibian species respond differentially to environmental changes	Richness was greatest in wetlands with forest permanency (Kolozsvary and Swihart 1999)
	If intact, continuous forest continues to be harvested, species that require ponds with longer hydro-periods for successful metamorphosis would be prone to population declines	Populations decline (Neckel-Oliveira and Lannoo 2007)
Deforestation (68)	Whereas forest specialists suffer direct negative effect from deforestation, generalist species can take advantage of forest alteration and the presence of farm animals	Population declines of specialist species (Cushman 2006; Furlani et al. 2009; Swift and Hannon 2010)
	Low density, population variability, and high mobility coupled with restricted habitat needs predispose woodland amphibians to local extinction caused by habitat fragmentation	Decrease in species richness (Gibbs 1998)
Fragmentation (346)	There is a negative correlation between the abundance of frogs in the matrix and their vulnerability to fragmentation; however, results varied with fragment size and species traits	Decrease in species abundance (Dixo and Metzger 2010)
<u>Pollution</u>		
Pesticides and chemical wastes (499)	Pesticides can cause variation in enzymatic levels among several tadpole species	It appears that a conversion of native ecosystems to soybean crops may lead to increased ecological risks for anuran amphibians (Davidson 2004; Sparling and Fellers 2007; Rohr et al. 2008; Lajmanovich et al. 2010)
Acid rain (24)		Low pH has a negative effect on body size (Frisbie and Wyman 1995)
Heavy metals (81): including iron, manganese, aluminum, mercury, cadmium, and beryllium	Cadmium inhibits acid secretion in stimulated frog gastric mucosa; Cu affects the liver metallothionein	No apparent effect on population dynamics (Lefcourt et al. 1998; Loumbourdis 2006; Cooper and Fortin 2010; Germino et al. 2010)
<u>Ultraviolet radiation (242)</u>		Lab experiments: UV-B has an overall negative effect in <i>Ambystoma mexicanum</i> . Proportion of deformed embryos varied through the year (Frías-Alvarez et al. 2010).
		Field experiments: “no differences in survival to hatching among UV-B-exposed and UV-B-shielded treatment” for <i>Rana muscosa</i> , <i>Bufo canorus</i> , or <i>Pseudacris regilla</i> (Vrederburg et al. 2010)
	UV-B (280–315 nm) can be easily absorbed by living cells and causes DNA mutation and/or cell death; induces lethal and sub-lethal effects on different ontogenetic phases of development	1.1% of the distribution of <i>Ambystoma macroleactylum</i> is exposed to lethal levels of radiation (Palen and Schindler 2010)
		Hatching success is unaffected by UV-B radiation. We suggest that UV-B radiation is an unlikely cause for declining populations of <i>Rana aurora</i> (Blaustein et al. 1996).
		Although UV-B radiation may not contribute to the population declines of all species, it may play a role in the population decline of some species (3 of 17) (Review of field experiments; Blaustein et al. 1998)
		By itself, UV-B causes no significant effects in <i>Hyla chrysoscelis</i> and <i>Rana blairi</i> (Bruner et al. 2002)
<u>Diseases</u>		
Fungi (332): principally chytrids	Focused principally in chytrids	Mass mortality of several species in Central America (Lips 1998, 1999; Lips et al. 2005; but see Kilpatrick et al. 2010)
	<i>Batrachochytrium dendrobatidis</i> (<i>Bd</i>) destroys keratinised mouthparts in anuran tadpoles, which are essential for feeding	<i>Bd</i> infection reduces foraging efficiency of anuran tadpoles by altering feeding kinematics and reduces host fitness (Venesky et al. 2010)

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Threat type	Proposed mechanism	Consequences or change in status (examples)
	Potentially disrupts osmoregulation or respiration across the skin of amphibians it infects, releases toxins into the host, or both	Results show inhibited rehydration in individuals exhibiting clinical signs of chytridiomycosis. However, aclinical chytridiomycosis does not severely affect amphibian skin function. From six (<i>Litoria raniformis</i>) individuals infected, only one died (Venesky et al. 2010).
Bacteria (105)	Opportunistic pathogen associated with cutaneous infections and nodular granulomatous skin lesions	Lab experiments: the infection does not cause death (Sánchez-Morgado et al. 2009)
	Red-legged disease (bacterial dermatosepticemia)	Can cause deaths (Densmore and Green 2007)
		No lethal consequences (Davis and Cecala 2010)
Viruses (110)		Can cause mass mortality (Daszak et al. 1999; Collins and Storfer 2003)
<u>Alien species</u>	Introduction of new predators	Extinction, but species can recover if the alien species is removed (Kats and Ferrer 2003)
<u>Climate variability</u>	Warmer temperatures than normal, especially during the dry season	No clear signal between temperature and population decline (Alexander and Eischeid 2010)
Droughts: La Niña, El Niño events	“Climate anomalies are not a feature of all extinctions, it is not unreasonable to expect that natural climate variability can interact with species life history and ecological community and population dynamics to contribute to extinctions”	Disappearance of <i>B. periglenes</i> (Anchukaitis and Evans 2010)
	Combination of factors, unusual warm weather, and the presence of <i>Bd</i>	Extinction (Barriouuevo and Ponssa 2008)
<u>Climate change</u>	Thermal-optimum for <i>Bd</i> growth	Extinction (Pounds et al. 2006; but see Appendix 3 for <i>cf</i> references)
	Climate envelope models	Extinction and displacement of distribution ranges (several authors, including Lawler et al. 2010 and Ochoa-Ochoa et al. 2012)

Appendix 2
List of scientific articles including the terms "Bufo periglenes" and/or "golden toad" resulting from the searches in both Scopus and the ISI Web of Knowledge, as of April 2010.

Authors	Year	Title	Journal	Example of population declining by climate change	Weather variability	Other	Example of unexplained population declining	Comments
Anchukaitis and Evans	2010	Tropical cloud forest climate variability and the demise of the Monteverde golden toad	<i>Proceedings of the National Academy of Sciences of the United States of America</i>			ENSO		
Barrionuevo and Ponssoa	2008	Decline of three species of the genus <i>Telmatobius</i> (Anura: Leptodactylidae) from Tucuman Province, Argentina	<i>Herpetologica</i>				Yes	
Blaustein and Wake et al.	1990	Declining amphibian populations: a global phenomenon	<i>Trends in Ecology and Evolution</i>				Yes	
Blaustein et al.	1996	DNA repair activity and resistance to solar UV-B radiation in eggs of the red-legged frog	<i>Conservation Biology</i>				Yes	
Blaustein et al.	1998	Effects of ultraviolet radiation on amphibians: field experiments	<i>American Zoologist</i>				Yes	
Blaustein et al.	1999	DNA repair and resistance to UV-B radiation in western spotted frogs	<i>Ecological Applications</i>				Yes	
Bruner et al.	2002	Developmental effects of ambient UV-B light and landfill leachate in <i>Rana blairi</i> and <i>Hyla chrysoscelis</i>	<i>Ecotoxicology and Environmental Safety</i>				Yes	
Buchanan	1994	Sexual dimorphism in <i>Hyla squirella</i> : chromatic and pattern variation between the sexes	<i>Copeia</i>			Sexual dimorphism		
Burrowes et al.	2004	Potential causes for amphibian declines in Puerto Rico	<i>Herpetologica</i>	Yes				
Bustamante et al.	2005	Changes in diversity of seven anuran communities in the Ecuadorian Andes	<i>Biotropica</i>					
Corser	2001	Decline of disjunct green salamander (<i>Aneides aeneus</i>) populations in the southern Appalachians	<i>Biological Conservation</i>		Yes			
Crump	1989	Life history consequences of feeding versus non-feeding in a facultatively non-feeding toad larva	<i>Oecologia</i>			Life history		
Crump et al.	1992	Apparent decline of the golden toad: underground or extinct?	<i>Copeia</i>			Too early to know		Because of its unpredictable and fluctuating breeding habitat (small pools prone to overflowing or

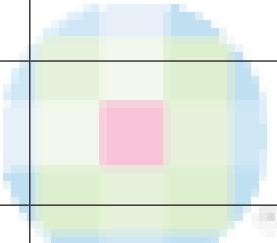
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Authors	Year	Title	Journal	Example of population declining by climate change	Weather variability	Other	Example of unexplained population declining	Comments
Daszak et al.	1999	Emerging infectious diseases and amphibian population declines	<i>Emerging Infectious Diseases</i>					desiccation). <i>B. periglenes</i> is a species vulnerable to vagaries of the weather. For this reason, the population might fluctuate widely in size due to variable recruitment success
Fogden	1996	Conservation of the golden toad: a brief history	<i>Herpetological Biology</i>					Hypothesised link with global extinction of golden toad, <i>Bufo periglenes</i>
Foster	1992	The international component of managing biological diversity	<i>57th North American wildlife and natural resources conference-crossroads of conservation: 500 years after Columbus</i>					Not reviewed as PDF was not available/accessible
Funk and Dunlap	1999	Colonization of high-elevation lakes by long-toed salamanders (<i>Ambystoma macrodactylum</i>) after the extinction of introduced trout populations	<i>Canadian Journal of Zoology</i>					Yes
Goerck	1997	Patterns of rarity in the birds of the Atlantic forest of Brazil	<i>Conservation Biology</i>					Small catastrophe or disease
Griffiths	2001	Conservation biology and declining amphibian populations	<i>Rivi Ichobiology</i>					Not reviewed as PDF was not available/accessible
Hays et al.	1996	Developmental responses of amphibians to solar and artificial UVB sources: a comparative study	<i>Photochemistry and Photobiology</i>					Yes
Hero et al.	2005	Ecological traits of declining amphibians in upland areas of eastern Australia	<i>Journal of Zoology</i>					Yes
Jacobson	1983	Short season of the golden toad	<i>International Wildlife</i>					Not reviewed as PDF was not available/accessible
Jacobson and Vandenberg	1991	Reproductive ecology of the endangered golden toad (<i>Bufo periglenes</i>)	<i>Journal of Herpetology</i>				Pet trade	Yes
Lips	1998	Decline of a tropical montane amphibian fauna	<i>Conservation Biology</i>					Chytridiomycosis
Lips	1999	Mass mortality and population declines of anurans at an upland site in western Panama	<i>Conservation Biology</i>					Yes

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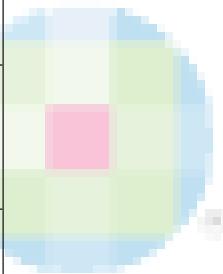
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Authors	Year	Title	Journal	Example of population declining by climate change	Weather variability	Other	Example of unexplained population declining	Comments
Lips et al.	2005	Amphibian population declines in Latin America: a synthesis	<i>Biotropica</i>				Chytridiomycosis*	Yes
Lizana and Pedraza	1998	The effects of UV-B radiation on toad mortality in mountainous areas of central Spain	<i>Conservation Biology</i>					Many hypotheses have been proposed to explain this decline: natural fluctuations of the populations (see references in Blaustein et al. 1994b), global changes in climate, long drought periods, or the depletion of the ozone layer
Nadkarni and Solano	2002	Potential effects of climate change on canopy communities in a tropical cloud forest: an experimental approach	<i>Oecologia</i>					
Nott et al.	1995	Extinctions rates: modern extinctions in the kilo-death range	<i>Current biology</i>	Yes		ENSO		
Pasmans et al.	2006	Amphibian decline: the urgent need for amphibian research in Europe	<i>Veterinary Journal</i>				Chytridiomycosis	
Pechman and Wilbur	1994	Putting declining amphibian populations in perspective: natural fluctuations and human impacts	<i>Herpetologica</i>					The classic example of a pandemic amphibian disease is <i>chytridiomycosis</i> , a fungal disease caused by <i>Batrachochytrium dendrobatidis</i> that is held responsible for massive amphibian die-offs and even for the extinction of several species worldwide, the most famous of which is the Costa Rican golden toad (<i>Bufo periglenes</i>)
Phillips	1990	Where have all the frogs and toads gone?	<i>Bioscience</i>				Natural causes (droughts)	The possibility remains that they are still present in underground or other retreats, and that their apparent disappearances represent extreme natural fluctuations
Pounds	1990	Disappearing gold	<i>BBC Wildlife</i>					Not reviewed as PDF was not available/accessible
Pounds and Crump	1994	Amphibian declines and climate disturbance: the case of the golden toad and the harlequin frog	<i>Conservation Biology</i>	Yes?		ENSO		
Pounds et al.	1997	Tests of null models for amphibian declines on a tropical mountain	<i>Conservation Biology</i>				Unusual weather	
Pounds et al.	2006	Widespread amphibian extinctions from epidemic disease driven by global warming	<i>Nature</i>	Yes				
Pounds et al.	1999	Biological response to climate change on a tropical mountain	<i>Nature</i>	Yes				

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Authors	Year	Title	Journal	Example of population declining by climate change	Weather variability	Other	Example of unexplained population declining	Comments
Savage	1972	The systematic status of <i>Bufo sinuus</i> with description of a new toad from western Panama	<i>Journal of Herpetology</i>					Description of <i>B. peripatus</i>
Vaira	2002	Anurans of a subtropical montane forest in northwestern Argentina: ecological survey and a proposed list of species of conservation concern	<i>Biodiversity and Conservation</i>			Yes		
Wake and Vredenburg	2008	Are we in the midst of the sixth mass extinction? A view from the world of amphibians	<i>Proceedings of the National Academy of Sciences of the United States of America</i>			Yes		



Appendix 3

A selection of papers citing Pounds et al. 2006. The papers were selected haphazardly, with no particular criteria in mind, but do not, strictly speaking, constitute a random sample. The sample of 92 cases represents approximately 23% of the articles, selected from 385 papers in January 2011, from Scopus.

Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Alarcón, J., G. Chaves, A. García-Rodríguez, and R. Vargas. 2010. Reconsidering extinction: rediscovery of <i>Incilius holridgei</i> (Anura: Bufonidae) in Costa Rica after 25 years. <i>Herpetological Review</i> 41(2):150–152						Yes	These disappearances have been attributed to different causes, including climate change (Pounds 1997, 2001) and emergent diseases such as chytridiomycosis (Lips et al. 2006), or the synergistic effect between these two agents (Pounds et al. 2006).
Arakaya, R.H., S.H.M. Butchart, G.M. Mace, S.N. Stuart, and C. Hilton-Taylor. 2006. Use and misuse of the IUCN red list criteria in projecting climate change impacts on biodiversity. <i>Global Change Biology</i> 12(11): 2037–2043					Yes		However, our discovery of a population of <i>Incilius holridgei</i> in a region with well documented chytridiomycosis (Puschendorf et al. 2006), allows a test of its vulnerability to this disease.
Agosta, S.J., N. Janz, and D.R. Brooks. 2010. How specialists can be generalists: resolving the “paradox” and implications for emerging infectious disease. <i>Zoologia</i> 27(2): 151–162					Yes		Recent studies demonstrate that climate change can affect species viability much faster than implied by range shifts, when it interacts with other factors.
Al-Attar, A.M. 2010. Hematological, biochemical and histopathological studies on marsh frog, <i>Rana ridibunda</i> , naturally infected with <i>Waltonella duboisii</i> . <i>International Journal of Zoological Research</i> 6(3): 199–213					Yes		The current emerging infectious disease (EID) crisis is “new”, only in the sense that this is the first such event that scientists have witnessed directly.
Almeida, J.B., M.N.E. Cazabon, L. Denpewolf, A. Hailey, R.M. Lehtinen, R.P. Mannette, K.T. Naranjit, and A.C.J. Roach. 2008. Presence of the chytrid fungus <i>Batrachochytrium dendrobatidis</i> in populations of the critically endangered frog <i>Mantophryne olmonae</i> in Tobago, West Indies. <i>EcoHealth</i> 5(1): 34–39					Yes		Chytridiomycosis is presently endemic in this species, with a prevalence of about 20% and no associated clinical disease [...] Thus although global warming might increase the susceptibility of montane amphibians by bringing their environments within the optimum temperature range of <i>B. dendrobatidis</i> this is unlikely in the lowland and lower-montane frog <i>M. olmonae</i> .

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Alford, R.A., K.S. Bradfield, and S.J. Richards. 2007. Ecology: global warming and amphibian losses. <i>Nature</i> 447(7144): E3–E4						Yes	We question the analysis of Pounds et al., which so far provides the only geographically broad test of this idea. Contrary to their working model 1, our Figures 1, 2 indicate that multiyear warm periods may be more important in amphibian declines than single warm years. By focusing on the latter, the authors' test could be inconclusive.
Alford, R.A. and S.J. Richards. 1997. Lack of evidence for epidemic disease as an agent in the catastrophic decline of Australian rain forest frogs. <i>Conservation Biology</i> 11(4): 1026–1029							
Altierattan, F. and D. Ebert. 2008. Genetic diversity of <i>Daphnia magna</i> populations enhances resistance to parasites. <i>Ecology Letters</i> 11(9): 918–928							
Altton, L.A., R.S. Wilson, and C.E. Franklin. 2010. Risk of predation enhances the lethal effects of UV-B in amphibians. <i>Global Change Biology</i> 16(2): 538–545					Yes		
Anchukaitis, K.J. and M.N. Evans. 2010. Tropical cloud forest climate variability and the demise of the Monteverde golden toad. <i>Proceedings of the National Academy of Sciences of the United States of America</i> 107(11): 5036–5040						Yes	Rather, the extinction of the Monteverde golden toad (<i>Bufo periglenes</i>) appears to have coincided with an exceptionally dry interval caused by the 1986–1987 El Niño event.
Berg, M.P., E. Toby Kiers, G. Driessens, M. van der Heijden, B.W. Kooi, F. Kuennen, M. Loeffing, et al. Adapt or disperse: understanding species persistence in a changing world. <i>Global Change Biology</i> 16(2): 587–598					Yes		Recent studies indicate that robustness of species interactions under climate change is determined by variation in the temperature sensitivity of their community components (Pounds et al. 2006).

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Bickford, D., S.D. Howard, D.J.J. Ng, and J.A. Sheridan. 2010. Impacts of climate change on the amphibians and reptiles of Southeast Asia. <i>Biodiversity and Conservation</i> 19(4): 1043–1062.			Yes				Additionally, increased metabolic rates often draw on energy normally allocated for maintenance (Fitzpatrick 1976; Scott and Fore 1995), resulting in increased susceptibility to disease (Pounds et al. 2006).
Blaustein, A.R. and A. Dobson. 2006. Extinctions: a message from the frogs. <i>Nature</i> 439(7073): 143–144			Yes				Pounds and colleagues provide compelling evidence that anthropogenic climate change has already altered transmission of a pathogen that affects amphibians, leading to widespread population declines and extinctions.
Blaustein, A.R. and P.T.J. Johnson. 2010. Conservation biology: when an infection turns lethal. <i>Nature</i> 465: 881–882			Yes				Intensity threshold of <i>B. dendrobatidis</i> varies across species or with environmental conditions, and what part is played by environmental cofactors such as climate change.
Botkin, D.B., H. Saxe, M.B. Araújo, R. Betts, R.H.W. Bradshaw, T. Cedhagen, P. Chesson, et al. 2007. Forecasting the effects of global warming on biodiversity. <i>BioScience</i> 57(3): 227–236			Yes (climatic variability)				... amphibian declines due to outbreaks of a pathogenic chytrid fungus (<i>Batrachochytrium dendrobatidis</i>) are related to the annual range of temperatures, not to the mean temperature.
Briggs, C.J., R.A. Knapp, and V.T. Vredenburg. 2010. Enzootic and epizootic dynamics of the chytrid fungal pathogen of amphibians. <i>Proceedings of the National Academy of Sciences of the United States of America</i> 107(21): 9695–9700			Yes				This model can easily incorporate the effects of temperature or other environmental conditions (such as water flow rate) on Bd growth.*
Brook, B.W., N.S. Sodhi, and C.J.A. Bradshaw. 2008. Synergies among extinction drivers under global change. <i>Trends in Ecology and Evolution</i> 23(8): 453–460			Yes				An excellent real-world example comes from the highland forests of Costa Rica, where 40% of 50 endemic frog and toad species disappeared following synchronous population crashes during the late 1980s. Recent work has linked these extinctions to an interaction between global warming and disease.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Brooks, D.R. and E.P. Hoberg. 2007. How will global climate change affect parasite-host assemblages? <i>Trends in Parasitology</i> 23(12): 571–574				Yes			Accelerated perturbation in global ecosystems can initiate events that link climate change, loss of biodiversity and emerging infectious diseases.
Brooks, T.M., S.J. Wright, and D. Sheil. 2009. Evaluating the success of conservation actions in safeguarding tropical forest biodiversity. <i>Conservation Biology</i> 23(6): 1448–1457	Yes						Little is known about other drivers of biodiversity loss within PAs. Examples include disease, which caused the extinction of the golden toad (<i>Ingerophrynus periglenes</i>) in Costa Rica's Reserva Biológica Monteverde.
Brujinzeel, L.A., M. Mulligan, and F.N. Scatena. 2011. Hydrometeorology of tropical montane cloud forests: emerging patterns. <i>Hydrological Processes</i> 25(3): 465–498	Yes						In recent years, climatic warming and drying related to global or regional climate change have become an increasingly important factor that can potentially threaten tropical montane cloud forest (TMCF) hydrological functioning, in addition to having a devastating effect on particularly vulnerable plant and animal groups like mosses and amphibians.
Bruno, J.F., E.R. Selig, K.S. Casey, C.A. Page, B.L. Willis, C.D. Harvell, H. Sweatman, et al. 2007. Thermal stress and coral cover as drivers of coral disease outbreaks. <i>Public Library of Science Biology</i> 5(6): 1220–1227				Yes			Temperature and climate change have also been implicated in plant and animal disease outbreaks in both terrestrial and aquatic habitats.
Buckley, L.B. and W. Jetz. 2007. Environmental and historical constraints on global patterns of amphibian richness. <i>Proceedings of the Royal Society B: Biological Sciences</i> 274(1614): 1167–1173					Yes		Amphibians have repeatedly been used as an indicator group for environmental change.*
Bush, M.B. and T.E. Lovejoy. 2007. Amazonian conservation: pushing the limits of biogeographical knowledge. <i>Journal of Biogeography</i> 34(8): 1291–1293				Yes			The synergism induced in Amazonia through simplifying ecological structure from the complexity of forest to the simplicity of soybean fields or ranchland, the increased probability of human-set fires, and complex ecological interactions.

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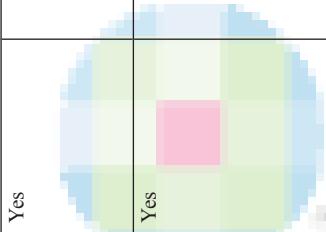
Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Example Quotes
Bustamante, H.M., L.J. Livo, and C. Carey. 2010. Effects of temperature and hydric environment on survival of the Panamanian golden frog infected with a pathogenic chytrid fungus. <i>Integrative Zoology</i> 5(2): 143–153		Yes					mediated by climate, e.g., bacterial diseases (Pounds et al. 2006).
Butler, G. 2010. Fungal sex and pathogenesis. <i>Clinical Microbiology Reviews</i> 23(1): 140–159	Yes						Pounds et al. (2006) propose a “climate-linked epidemic hypothesis,” or, more specifically, a “chytrid-thermal-optimum hypothesis.”
Calosi, P., D.T. Bilton, and J.I. Spicer. 2008. Thermal tolerance, acclimatory capacity and vulnerability to global climate change. <i>Biology Letters</i> 4(1): 99–102	Yes						Others cause disease in animals, such as the chytrid species <i>Batrachochytrium dendrobatidis</i> , which is devastating the global amphibian population.
Cannatella, D.C. 2008. Comment on ‘Habitat split and the global decline of amphibians’. <i>Science</i> 320: 874d–874d				Yes			During periods of rapid climate change, taxa that are unable to shift their geographical ranges are particularly at risk from extinction (Pounds et al. 2006).
Carnaval, A.C. and J.M. Bates. 2007. Amphibian DNA shows marked genetic structure and tracks Pleistocene climate change in northeastern Brazil. <i>Evolution</i> 61(12): 2942–2957							Amphibians are important indicators of environmental degradation and climate change.
Carvalho, S.B., J.C. Brito, E.J. Crespo, and H.P. Possingham. 2010. From climate change predictions to actions: conserving vulnerable animal groups in hotspots at a regional scale. <i>Global Change Biology</i> 16(12): 3257–3270							Our data show <i>B. dendrobatidis</i> to be present in Brazil in the early 1980s. When tied to Heyer et al.’s (1988) and Weygoldt’s (1989) observations on local climate anomalies, our results are consistent with a hypothesis of a climate-linked epidemic event leading to amphibian declines (Pounds et al. 2006).
Casadevall, A. and L.A. Pirofski. 2007. Accidental virulence, cryptic pathogenesis, mar提ans, lost hosts and the pathogenicity of environmental microbes. <i>Eukaryotic Cell</i> 6(12): 2169–2174				Yes			Climate warming is projected to induce the spread of chytridiomycete fungus.
							The ongoing decimation of amphibian populations by a chytrid fungus may reflect a similar phenomenon, whereby ecological changes might select for variants with enhanced virulence.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Chown, S.L., K.J. Gaston, M. van Kleunen, and S. Clusella-Trullas. 2010. Population responses within a landscape matrix: a macrophysiological approach to understanding climate change impacts. <i>Evolutionary Ecology</i> 24(3): 601–616	Yes						Although the ultimate causes of amphibian declines in tropical Central America remain the subject of debate (e.g. Pounds et al. 1999, 2006; Rohr et al. 2008), changes in water availability owing to global temperature change and local habitat destruction are important (Rovito et al. 2009).
Chown, S.L. and J.S. Terblanche. 2006. Physiological diversity in insects: ecological and evolutionary contexts. <i>Advances in Insect Physiology</i> 33: 50–152	Yes						In many cases, climate change effects are negative and have either resulted in or are predicted to give rise to species extinctions.
Cisneros-Heredia, D.F., J. Delia, M.H. Yáñez-Muñoz, and H.M. Ortiga-Andrade. 2010. Endemic Ecuadorian glassfrog <i>Cochranella mache</i> is critically endangered because of habitat loss. <i>Oryx</i> 44(1): 114–117							Yes
Clark, D.A. 2007. Detecting tropical forests' responses to global climatic and atmospheric change: current challenges and a way forward. <i>Biotropica</i> 39(1): 4–19							Diseases and global warming have been linked to some of these declines but the causes of most remain poorly understood.
Coloma, L.A., S. Lötters, W.E. Duellman, and A. Miranda-Leiva. 2007. A taxonomic revision of <i>Atelopus pachydermus</i> and description of two new (extinct?) species of <i>Atelopus</i> from Ecuador (Anura: Bufonidae). <i>Zootaxa</i> 1557: 1–32	Yes						As recently illustrated by an analysis of frog extinctions in Costa Rica (Pounds et al. 2006), elevational transects of continuous tropical forest offer an important opportunity for detecting the effects of climate change on tropical forest plants.
Contreras, V., E. Martínez-Meyer, E. Valiente, and L. Zambrano. 2009. Recent decline and potential distribution in the last remnant area of the microendemic Mexican	Yes						Ecuadorian amphibian species are under categories of extinction risk, we emphasize on the challenge of a rapid response and fundamental changes in policies and actions that are required in order to address the amphibian crisis... given the novel threats mostly imposed by global warming and pathogens.
							Climate change has also been identified as an important indirect threat for amphibian populations in recent decades.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Example Quotes
axolotl (<i>Ambystoma mexicanum</i>). <i>Biological Conservation</i> 142(12): 2881–2885	Cooper, N., J. Bielby, G.H. Thomas, and A. Purvis. 2008. Macroecology and extinction risk correlates of frogs. <i>Global Ecology and Biogeography</i> 17(2): 211–221		Yes (changes in the environment)				These environmental variables may also be linked directly to extinction risk in frogs since these taxa are very sensitive to changes in the environment (Pounds et al. 2006) that can also increase their susceptibility to other threats, for example the chytrid fungus.
Corey, S.J. and T.A. Waite. 2008. Phylogenetic autocorrelation of extinction threat in globally imperilled amphibians. <i>Diversity and Distributions</i> 14(4): 614–629			Yes				
Crausbay, S.D. and S.C. Hotchkiss. 2010. Strong relationships between vegetation and two perpendicular climate gradients high on a tropical mountain in Hawai'i. <i>Journal of Biogeography</i> 37(6): 1160–1174			Yes				Some of the few studies that do show evidence of tropical biological response also demonstrate that response to climate change can be complicated by powerful secondary effects, including fire, disease and invasive species (Hemp 2005; Pounds et al. 2006).
Crutzen, P.J. 2006. Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? <i>Climatic Change</i> 77(3): 211–219			Yes				Already major species extinctions by current climate warming have been reported by Pounds et al.
Dalek, H.J., D.N. Koons, and P.B. Adler. 2010. Can life-history traits predict the response of forb populations to changes in climate variability? <i>Journal of Ecology</i> 98(1): 209–217			Yes				
Daly, G.L., Y.D. Lei, C. Teixeira, D.C.G. Muir, L.E. Castillo, and F. Wania. 2007. Accumulation of current-use pesticides in neotropical montane forests. <i>Environmental Science and Technology</i> 41(4): 1118–1123			Yes				Even though pathogens in combination with global warming have recently been implicated in the decline of amphibian populations in the Neotropics, this does not exclude a potential role of contaminants in this disturbing phenomenon.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Deichmann, J.I., G.B. Williamson, A.P. Lima, and W.D. Allmon. 2010. A note on amphibian decline in a central Amazonian lowland forest. <i>Biodiversity and Conservation</i> 19(12): 3619–3627	Yes						Enigmatic decline has been attributed to a number of proximal causes including climate change.
Eugster, W., R. Burkard, F. Holwerda, F.N. Scatena, and L.A. Bruijnzeel. 2006. Characteristics of fog and fogwater fluxes in a Puerto Rican elfin cloud forest. <i>Agricultural and Forest Meteorology</i> 139(3): 288–306				Environmental conditions			Cloud forests have been reported to be very susceptible to changes in environmental conditions.
Fouquet, A., G.F. Ficetola, A. Haigh, and N. Gemmell. 2010. Using ecological niche modelling to infer past, present and future environmental suitability for <i>Leiopelma hochstetteri</i> , an endangered New Zealand native frog. <i>Biological Conservation</i> 143(6): 1375–1384	Yes						This has been the case for New Zealand native frogs (<i>Leiopelma</i>) with serious declines due to a climate driven epidemic of chytridiomycosis (Bell et al. 2004a; Pounds et al. 2006).
Franco, A.M.A., J.K. Hill, C. Kitschke, Y.C. Collingham, D.B. Roy, R. Fox, B. Huntley, et al. 2006. Impacts of climate warming and habitat loss on extinctions at species' low-latitude range boundaries. <i>Global Change Biology</i> 12(8): 1545–1553	Yes						Extinctions will often be driven by climate change and other threats acting in concert species.
Gachon, C.M.M., T. Sime-Ngando, M. Strittmatter, A. Chambouvet, and G.H. Kim. 2010. Algal diseases: spotlight on a black box. <i>Trends in Plant Science</i> 15(11): 633–640				Yes			Climate change already affects disease patterns worldwide, and is incriminated in massive sudden extinctions (e.g. ‘frog killer fungus’).
Gamer, T.W.J., J.M. Rowcliffe, and M.C. Fisher. 2011. Climate change, chytridiomycosis or condition: an experimental test of amphibian survival. <i>Global Change Biology</i> 17(2): 667–675						Yes	The amphibian host/ <i>Barachochytrium dendrobatis</i> (Bd) parasite system is considered by many to be strongly influenced by changes in environmental temperature (Pounds et al. 2006; Boch et al. 2007; Muths et al. 2008, but see Lips et al. 2008); evidence for this is equivocal.
Gilman, S.E., M.C. Urban, J. Tewksbury, G.W. Gilchrist, and R.D. Holt. 2010. A framework for				Yes			Empirical evidence suggests that climate-driven changes in interacting species, including...

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
community interactions under climate change. <i>Trends in Ecology and Evolution</i> 25(6): 325–331							pathogen prevalence, phenologies or behaviors of competitors or mutualists, predator or competitor efficiency, and changes in the body size of prey can drive local extinctions, but surprisingly few general patterns have emerged.
Grasso, R.L., R.M. Coleman, and C. Davidson. 2010. Palatability and antipredator response of Yosemite Toads (<i>Anaxyrus canorus</i>) to nonnative Brook Trout (<i>Salvelinus fontinalis</i>) in the Sierra Nevada Mountains of California. <i>Copeia</i> 3: 457–462	Yes						
Jiguet, F., R. Julliard, C.D. Thomas, O. Dehorter, S.E. Newson, and D. Courvet. 2006. Thermal range predicts bird population resilience to extreme high temperatures. <i>Ecology Letters</i> 9(12): 1321–1330	Yes						Projected responses of species to climate change provide strong evidence that anthropogenic climate change represents a serious threat to biodiversity.
Johnson, P.T.J. 2006. Amphibian diversity decimation by disease. <i>Proceedings of the National Academy of Sciences of the United States of America</i> 103(9): 3011–3012				Yes			Recent work by Pounds et al. (12), for example, suggests that temperature shifts promote Batrachochytrium infection at certain elevations and may therefore have indirectly driven the loss of numerous harlequin frog species in Central and South America.
Karvonen, A., P. Rintamäki, J. Jokela, and E.T. Valtonen. 2010. Increasing water temperature and disease risks in aquatic systems: climate change increases the risk of some, but not all, diseases. <i>International Journal for Parasitology</i> 40(13): 1483–1488			Yes				The risk of parasite and pathogen infections may also increase.
Kippatrick, A.M., C.J. Briggs, and P. Daszak. 2010. The ecology and impact of chytridiomycosis: an emerging disease of amphibians. <i>Trends in Ecology and Evolution</i> 25(2): 109–118						Yes	
Koch, P.L. and A.D. Barnosky. 2006. Late Quaternary extinctions: state of the debate. <i>Annual Review of Ecology, Evolution and Systematics</i> 37: 215–250				Yes			Global extinctions of some smaller animals are attributed to current warming.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Laurance, W.F. 2008. Global warming and amphibian extinctions in eastern Australia. <i>Austral Ecology</i> 33(1): 1–9			Yes				Rising temperatures could also alter other features of montane areas, such as... the diversity and virulence of pathogens.
Lawler, J.J., S.L. Shafer, and A.R. Blaustein. 2010. Projected climate impacts for the amphibians of the western hemisphere. <i>Conservation Biology</i> 24(1): 38–50			Yes				
Lovejoy, T.E. 2006. Protected areas: a prism for a changing world. <i>Trends in Ecology and Evolution</i> 21(6): 329–333			Yes				It is a complex multi-factorial situation involving pollutants, habitat destruction, climate change and an epidemic pathogen (a chytrid fungus), with increasing evidence of synergism among these.
Loyola, R.D., C.G. Becker, U. Kubota, C.F.B. Haddad, C.R. Fonseca, and T.M. Lewinsohn. 2008. Hung out to dry: choice of priority ecoregions for conserving threatened neotropical anurans depends on life-history traits. <i>Public Library of Science ONE</i> 3(5): e2120	Yes						
Mainka, S.A. and G.W. Howard. 2010. Climate change and invasive species: double jeopardy. <i>Integrative Zoology</i> 5(2): 102–111		Yes					Climate is changing before our eyes. Species extirpations (local extinctions) and extinctions of amphibians have been linked with climate change.
McGinnity, P., E. Jennings, E. DeEyo, N. Allott, P. Samuelsson, G. Rogan, K. Whelan, et al. 2009. Impact of naturally spawning captive-bred Atlantic salmon on wild populations: depressed recruitment and increased risk of climate-mediated extinction. <i>Proceedings of the Royal Society B: Biological Sciences</i> 276(1673): 3601–3610			Yes				
Meegaskumbura, M., K. Manamendra-Arachchi, C.J. Schneider, and R. Pethiyagoda. 2007. New species amongst Sri Lanka's extinct shrub frogs (Amphibia: Rhacophoridae: Philautus). <i>Zootaxa</i> 1397: 1–15			Yes				Climate-driven epidemic disease.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Mendelson, J.R., K.R. Lips, J.E. Difendorfer, R.W. Gagliardo, G.B. Rabb, J.P. Collins, P. Daszak, et al. 2006. Biodiversity: confronting amphibian declines and extinctions. <i>Science</i> 313(5783): 48–48			Yes				Global climate change may be encouraging local conditions ideal for Bd's persistence and/or spread.
Miller, F.J. 2007. The marine inorganic carbon cycle. <i>Chemical Reviews</i> 107(2): 308–341	Yes						The increase in the temperature may cause the extinction of animals.
Murray, K.A., L.F. Sherratt, R. Speare, and H. McCallum. 2009. Impact and dynamics of disease in species threatened by the amphibian chytrid fungus, <i>Batrachochytrium dendrobatidis</i> . <i>Conservation Biology</i> 23(5): 1242–1252						Yes	There is no evidence that climatic anomalies caused these declines, either directly or as suggested by current models of climate-linked disease outbreaks.
Olivier, A., C. Barbraud, E. Rosech, C. Germain, and M. Cheylan. 2010. Assessing spatial and temporal population dynamics of cryptic species: an example with the European pond turtle. <i>Ecological Applications</i> 20(4): 993–1004			Yes (but climatic anomalies)				Climate anomalies have been proposed as triggers of die-offs by providing opportunities for fatal chytrid outbreaks.
Page, R.A. and M.J. Ryan. 2006. Social transmission of novel foraging behaviour in bats: frog calls and their referents. <i>Current Biology</i> 16(12): 1201–1205					Yes		The flexibility, exploratory behavior, and social learning we document in this study endow the bats with the potential to respond rapidly to changes in prey conditions. With the catastrophic and worldwide decline of amphibians (Pounds et al. 2006), their predators' ability to track such changes becomes increasingly critical.
Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. <i>Annual Review of Ecology Evolution and Systematics</i> 37: 637–669					Yes		Pounds et al. (2006) hypothesised that recent trends toward warmer nights and increased daytime cloud cover have shifted mid-elevation sites (1000–2400 m), where the preponderance of extinctions have occurred, into thermally optimum conditions for the chytrid fungus, <i>Batrachochytrium dendrobatidis</i> .

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Pauli, H., M. Gottfried, K. Reiter, C. Klettner, and G. Grabherr. 2007. Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994–2004) at the GLORIA* master site Schrankogel, Tyrol, Austria. <i>Global Change Biology</i> 13(1): 147–156	Yes						Climate warming-associated shifts or extirpations at the rear edges of species have been detected.
Pedersen, A.B., K.E. Jones, C.L. Nunn, and S. Altizer. 2007. Infectious diseases and extinction risk in wild mammals. <i>Conservation Biology</i> 21(5): 1269–1279	Yes						
Pihla, H., M. Luoto, M. Piha, and J. Merilä. 2007. Anuran abundance and persistence in agricultural landscapes during a climatic extreme. <i>Global Change Biology</i> 13(1): 300–311	Yes						Global climate change has been shown to be negatively related with the survival, distribution and abundance of amphibians, as well as influence their breeding phenology.
Pounds, J.A., A.C. Camaral, R. Puschendorf, C.F.B. Haddad, and K.L. Masters. 2006. Responding to amphibian loss. <i>Science</i> 314(5805): 1541–1542					Yes		Evidence suggests that climate change and other factors may contribute to declines by triggering disease outbreaks, which might travel varying distances in wavelike patterns.
Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, et al. 2007. Ecology–Pounds et al. reply. <i>Nature</i> 447: E5–E6					Yes		
Puschendorf, R., and F. Bolívar. 2006. Detection of <i>Batrachochytrium dendrobatis</i> in <i>Eleutherodactylus fitzingeri</i> : effects of skin sample location and histologic stain. <i>Journal of Wildlife Diseases</i> 42(2): 301–306							The chytrid fungus <i>Batrachochytrium dendrobatis</i> has been implicated in amphibian declines around the world.
Puschendorf, R., F. Castañeda, and J.R. McCranie. 2006. Chytridiomycosis in wild frogs from Pico Bonito National Park, Honduras. <i>EcoHealth</i> 3(3): 178–181					Yes		Pounds et al. (2006) found that most of the missing harlequin frog species vanished in warmer years than average years.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Raffel, T.R., J.R. Rohr, J.M. Kiesecker, and P.J. Hudson. 2006. Negative effects of changing temperature on amphibian immunity under field conditions. <i>Functional Ecology</i> 20(5): 819–828			Yes				Increased infection risk due to warming trends has recently been implicated in the extinction of many tropical frog species.
Ransey, J.P., L.K. Reinert, L.K. Harper, D.C. Woodhams, and L.A. Rollins-Smith. 2010. Immune defences against <i>Batrachochytrium dendrobatidis</i> , a fungus linked to global amphibian declines, in the South African clawed frog, <i>Xenopus laevis</i> . <i>Infection and Immunity</i> 78(9): 3981–3992			Yes				
Reading, C.J. 2007. Linking global warming to amphibian declines through its effects on female body condition and survivorship. <i>Oecologia</i> 151(1): 125–131			Yes				What has not been demonstrated, however, is how the link between 'global warming' and amphibian declines operates (Collins and Storfer 2003) though Pounds et al. (2006) have suggested that temperatures in many highland areas are shifting towards the growth optimum for the pathogenic chytrid fungus (<i>Batrachochytrium dendrobatidis</i>), thereby encouraging outbreaks.
Rodder, D., M. Veith, and S. Lotters. 2008. Environmental gradients explaining the prevalence and intensity of infection with the amphibian chytrid fungus: the host's perspective. <i>Animal Conservation</i> 11(6): 513–517			Yes				
Rohr, J.R., T.R. Raffel, J.M. Romanic, H. McCallum, and P.J. Hudson. 2008. Evaluating the links between climate, disease spread and amphibian declines. <i>Proceedings of the National Academy of Sciences of the United States of America</i> 105(45): 17436–17441			Yes				

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Example Quotes
Rosa, I.D., F. Simoncelli, A. Fagotti, and R. Pascolini. 2007. Ecology: the proximate cause of frog declines? <i>Nature</i> 447(7144): E4–E5						Yes	We therefore think that the focus by Pounds et al. (2006) on a single pathogen is hard to justify because the host-parasite ecology is at present so poorly understood.
Shearer, C.A., E. Descals, B. Kohlmeyer, J. Kohlmeyer, L. Marvanová, D. Padgett, D. Porter, et al. 2007. Fungal biodiversity in aquatic habitats. <i>Biodiversity and Conservation</i> 16(1): 49–67		Yes					This chytrid, <i>Batrachochytrium dendrobatidis</i> , parasitizes and kills amphibians (Berger et al. 1999) and may be responsible, along with changes in environmental factors such as temperature (Pounds et al. 2006), for the global amphibian decline.
Smith, K.G., K.R. Lips, and J.M. Chase. 2009. Selecting for extinction: nonrandom disease-associated extinction homogenizes amphibian biotas. <i>Ecology Letters</i> 12(10): 1069–1078						Yes	Recent analyses indicate that there is presently little direct evidence for a role of climate as the widespread, proximate cause of amphibian declines in Lower Central America (cf. Pounds et al. 2006; Lips et al. 2008; Rohr et al. 2008).
Tylianakis, J.M., R.K. Didham, J. Bascompte, and D.A. Wardle. 2008. Global change and species interactions in terrestrial ecosystems. <i>Ecology Letters</i> 11(12): 1351–1363					Yes (but ENSO)		
Underwood, E.C. and B.L. Fisher. 2006. The role of ants in conservation monitoring: if, when and how. <i>Biological Conservation</i> 132(2): 166–182					Yes		
Voyles, J., E.B. Rosenblum, and L. Berger. 2011. Interactions between Batrachochytrium dendrobatidis and its amphibian hosts: a review of pathogenesis and immunity. <i>Microbes and Infection</i> 13(1): 25–32					Yes		The importance of temperature also prompted the hypothesis that global climate change might create optimal thermal conditions for disease spread (i.e. the chytrid thermal optimum hypothesis).
Wasonga, D.V., A. Bekele, S. Lotters, and M. Balakrishnan. 2007. Amphibian abundance and diversity in Meru National Park, Kenya. <i>African Journal of Ecology</i> 45(1): 55–61					Yes		The survival of the amphibian fauna all over the world is under threat as a result of a variety of causes, apparently related to global change.

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Article	Example of vulnerability towards chytridiomycosis	Example of vulnerability towards climate change	Example of climate change promoting chytridiomycosis	No cause mentioned	Example of APD but no related cause	Example of challenging the CTOH	Quotes
Williams, S.E., L.P. Shoo, J.L. Isaac, A.A. Hoffmann, and G. Langham. 2008. Towards an integrated framework for assessing the vulnerability of species to climate change. <i>Public Library of Science Biology</i> 6(12): 2621–2626	Yes						
Witte, C.L., M. Sredl, A.S. Kane, and L.L. Hungerford. 2008. Epidemiologic analysis of factors associated with local disappearances of native ranid frogs in Arizona. <i>Conservation Biology</i> 22(2): 375–383	Yes						
Woodhams, D.C., R.A. Alford, C.J. Briggs, M. Johnson, and L.A. Rollins-Smith. 2008. Life-history trade-offs influence disease in changing climates: strategies of an amphibian pathogen. <i>Ecology</i> 89(6): 1627–1639	Yes						
Woodhams, D.C., K. Ardipadja, R.A. Alford, G. Marantelli, L.K. Reinert, and L.A. Rollins-Smith. 2007. Resistance to chytridiomycosis varies among amphibian species and is correlated with skin peptide defenses. <i>Animal Conservation</i> 10(4): 409–417	Yes						
Woodhams, D.C., N. Kenyon, S.C. Bell, R.A. Alford, S. Chen, D. Billheimer, Y. Shyr, et al. 2011. Adaptations of skin peptide defences and possible response to the amphibian chytrid fungus in populations of Australian green-eyed treefrogs, <i>Litoria genimaculata</i> . <i>Diversity and Distributions</i> 16(4): 703–712	Yes (but environmental co-factors)						Environmental cofactors vary among populations. These may be particularly important in the dynamics of chytridiomycosis.
Zambrano, L., E. Vega, M.I.G. Herrera, E. Prado, and V.H. Reynoso. 2007. A population matrix model and population viability analysis to predict the fate of endangered species in highly managed water systems. <i>Animal Conservation</i> 10(3): 297–303							Yes

Acronyms: amphibian population decline (APD), and chytrid-thermal-optimum hypothesis (CTOH). * Indicates mis-citation of Pounds et al. 2006