Research Directions: One Health

www.cambridge.org/one

Impact Paper

Cite this article: Hopkins C, Lesbarrères D, Claunch N, Emmenegger E, Hardy B, Torres-Sánchez M, Stark T, Julian A, McGrath-Blaser S, Parker-Graham CA, Haman K, Morgan A, and Miller DL (2024). Balancing the scales: Including under-represented herptile species in a One Health approach. *Research Directions: One Health*. **2**, e17, 1–10. https://doi.org/10.1017/one.2024.14

Received: 11 July 2024
Revised: 24 October 2024
Accepted: 3 November 2024

Keywords:
Herptile; One Health; reptiles; amphibians; ethnoherpetology

Corresponding author:
Debra L. Miller; Email: dmille42@utk.edu

Balancing the scales: Including under-represented herptile species in a One Health approach

Camille Hopkins[1], David Lesbarrères[2,3], Natalie Claunch[4], Eveline Emmenegger[5], Bennett Hardy[6], María Torres-Sánchez[7], Tariq Stark[8], Angela Julian[9], Sarah McGrath-Blaser[4], Christine A. Parker-Graham[10], Katie Haman[11], Ashley Morgan[12] and Debra L. Miller[12]

[1]United States Geological Survey Headquarters, Ecosystems Mission Area, Reston, VA, USA; [2]Environment and Climate Change Canada, Ottawa, ON, Canada; [3]Laboratoire Biodiv'AG, UFR Sciences, Université d'Angers, Angers, France; [4]Department of Biology, University of Florida, Gainesville, FL, USA; [5]Western Fisheries Research Center, United States Geological Survey, Seattle, WA, USA; [6]Schmid College of Science and Technology, Chapman University, Orange, CA, USA; [7]Department of Biodiversity, Ecology and Evolution, Complutense University of Madrid, Madrid, Spain; [8]Amphibian and Fish Conservation Netherlands (RAVON), BK Nijmegen, The Netherlands; [9]Amphibian and Reptile Groups of the UK (ARG UK), Oxford, UK; [10]Pacific Region Fish Health Program, United States Fish and Wildlife Service, Lacey, WA, USA; [11]Washington Department of Fish and Wildlife, Olympia, WA, USA and [12]One Health Initiative, University of Tennessee, Knoxville, TN, USA

Abstract

The One Health High-Level Expert Panel's definition of One Health includes optimizing the health of people, animals (wild and domestic) and ecosystems. For many One Health practitioners, wildlife that can spread zoonoses are the focus, particularly if they can come in contact with people. However, ecosystem health is often best-indicated by less-encountered species, for instance, amphibians and reptiles. This review highlights how these taxa can benefit human health and well-being, including cultural significance, as well as their impact on plant, animal and environmental health. We highlight current challenges to the health of these species and the need to include them in the One Health Joint Action Plan. We conclude with a call to action for inclusion of amphibians and reptiles in a One Health approach.

Introduction

The Millennium Ecosystem Assessment, a United Nations report, discussed four categories of ecosystem services: provisioning, regulating, supporting and cultural services. The public may not understand that the benefits they obtain from ecosystems are not just due to the wildlife they see, but also the cryptic wildlife they may not notice, including reptiles and amphibians. Herpetofauna (amphibians and reptiles, also described as herps or herptile species) contribute to all of the ecosystem services (Valencia-Aguilar et al., 2013); yet few people recognize that human health and well-being is tied to the diversity and health of herptile species. The One Health High-Level Expert Panel (OHHLEP), assembled and endorsed by a quadripartite coalition consisting of the Food and Agriculture Organization (FAO), World Health Organization (WHO), World Organization for Animal Health (WOAH) and United Nations Environment Program (UNEP), defines One Health as "an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems" (One Health High-Level Expert Panel (OHHLEP) et al. 2022). Even when tackling complex problems using a One Health approach, multi-sectoral teams often focus on wildlife that are commonly encountered or observed by people (Cunningham et al., 2017), ignoring the multiple ways in which human health is tied to the less-encountered reptiles and amphibians. Healthy forests, wetlands and other ecosystems inhabited by herps benefit human health and well-being (e.g., source of clean air, clean water and food security). Amphibians are indicators of ecosystem health and serve as important sources of energy for food webs. For example, salamanders are the greatest sources of biomass or food for forest vertebrates in parts of North America (Semlitsch et al., 2014). So why is herptile health rarely integrated into a One Health approach? One of the key underlying principles of One Health is equity between sectors and disciplines. Following a "Herps and One Health" workshop at the 2022 inaugural Global Amphibian and Research Disease Conference, the participants delved deeper into the topic and completed this manuscript. Here we review some illustrative examples that provide evidence supporting the critical need to integrate herptile species health into an equitable One Health approach and highlight the contributions of herpetofauna to ecosystem, plant, animal and human health. We conclude with a call to action that highlights the integral role of herps in the Quadripartite One Health Joint Plan of Action.

Herps are indicators of ecosystem health

Reptiles and amphibians contribute to nutrient cycling, seed dispersal and pollination, pest control and energy conversion by ingesting plants and serving as food for predators (Hocking and Babbitt, 2014). Ectotherms, including reptiles and amphibians, are sensitive to environmental change and can serve as indicators of ecosystem health. As such, herps are critical to the United Nations Sustainable Development Goals #6 (clean water) and #15 (life on land) ('2024). The 2022 SDG report highlighted that (1) over 85% of the world's wetlands have been lost over the last 300 years (SDG #6) and (2) ten million hectares of intact forest are lost to land-use change every year (SDG #15). Because herptile biodiversity and health are impacted by habitat degradation and loss, these species represent key bio-indicators of ecosystem health. For example, geographic herptile functional group analyses were used in South Korea to guide the identification of biodiversity hotspots and indicate ecosystem health (Jeon et al., 2023). Similarly, China (Li et al., 2017), the United States (Adams and Muths, 2019) and other countries monitor herptile biodiversity to assess ecosystem health.

Herps and plant health

Amphibians and reptiles contribute to overall plant health through seed dispersal and pollination and as predators of crop pests (Valencia-Aguilar et al., 2013; Hocking and Babbitt, 2014). Herps can serve as pollinators when they move from flower to flower, drinking nectar and inadvertently transporting pollen for example *Xenohyla truncate* (de-Oliveira-Nogueira et al., 2023). In another example, the dusky lizard (*Liolaemus belii*) has been shown to be an important seed disperser of a barberry species native to Chile (Celedón-Neghme et al., 2008). This is significant because berberine, a popular dietary supplement with medicinal benefits, comes from barberry plant species. As predators, 78% of the South American toad's (*Rhinella arenarum*) diet includes arthropods that damage crops, and it is reported that the loss of *R. arenarum* and other amphibians will decrease this biological pest control for soybean crops (Attademo et al., 2005).

Herps and animal health

An interdependency exists between herpetofauna and other wildlife in their ecosystems. Larval amphibians can occur in incredibly high densities in some ecosystems and are likely to have significant effects on ecosystem functions, including primary productivity, through changes in the food web (Seale, 1980). They can act as primary consumers, detritivores, predators and even cannibals, improving water quality of both wild and farm ponds and in turn affecting domestic and farm animal health (Gibbons et al., 2006). Reptiles can also impact farm animal health. For example, Caiman species can control aquatic snails that serve as intermediate hosts for the trematode *Fasciola hepatica*, which damages the liver of infected cattle and sheep (Valencia-Aguilar et al., 2013). Herps can also be impacted as a cascade effect; for example, declines in neotropical frogs and tadpoles can result in significant declines of frog-eating snake populations (Zipkin et al., 2020).

Herps and human health

One of the most common notions connecting herptile species and human health is the detrimental presence of poison in amphibians and reptiles. Venomous species inject toxin by bite (e.g., cobra) or sting, while humans handling poisonous species may ingest, inhale or absorb toxins (e.g., poison dart frog). Injection or ingestion of toxins may result in illness or death. Furthermore, while herptile species can be a food source for humans (e.g., frog legs), there is concern over their potential to carry multidrug-resistant strains of important human pathogens like *E. coli* and *Acinetobacter* spp. similar to other meats (Morrison and Rubin, 2020). The mechanisms of such antimicrobial resistance in wildlife species remain unclear but may be tied to persistence of antimicrobial residues in domestic animals and the environment (Vittecoq et al., 2016). Given the gravity of emerging antimicrobial resistance, further investigation into drug-resistant microbes and wild herpetofauna is warranted. Human health and well-being benefit from herptile species, including the development of cancer therapies, cardiovascular therapies and other treatments (Table 1; Bordon et al., 2020).

Cultural benefits of herptile species

Urbanized societies are becoming more disconnected from nature and wildlife, including amphibians and reptiles. Yet, the One Health approach reminds us that we are all linked, including the importance that herps play throughout various cultures. Ethnoherpetology documents the human connection to herptile species as represented in ancient culture vestiges and folklore, with some cultural traditions persisting to this day (Crump, 2024); in the earliest human civilizations, amphibians and reptiles were deities. Here, we detail the importance of some herpetological species across past and present cultures.

Turtles

Turtles play a prominent role in the creation story of several indigenous peoples and tribes across the Americas. The Iroquoi, Ojibwe, Algonquin, Cree and others believe that North and Central America were formed on the back of a large turtle that Great Mother Aataentsic landed on after falling through a hole in the sky (Pearce, 2005). Contemporarily, turtles are also responsible for ecotourism booms to watch and participate in the conservation of sea turtle species during nesting on beaches (Jacobson and Lopez, 1994).

Snakes

Many traits that are associated with snakes have been likened to human traits - for example the sinuous coils of a snake's body are often related to human hair, becoming a symbol of richness, wealth and prosperity in 4th century Roman culture (Lazarou, 2018). In one Aboriginal dreaming story, the rainbow serpent is referred to as a creator and, like the rainbow, frequently associated with water and rainfall. The rainbow serpent is a widespread tradition in pre-colonial Australian societies, depicted in the rock art of the Waayni people from Northwestern Queensland (Taçon, 2008).

Even to this day, the rod or staff of the Greco-Roman god of healing and medicine, Asclepius, is used as a symbol of health care. Evidence suggests that the non-venomous European Aesculapian snake (*Zamenis longissimus*), which derives its name from this god, was allowed to roam freely in "healing temples" in ancient Greece

Table 1. Examples of connections between herptile species and human health

Herptile Class	Connections to Human Health	References
Amphibians	*Direct connections*	
	• *In the 1930s, Xenopus laevis* were taken from the wild and used to develop a human pregnancy test. Captive rearing was then utilized to sustain a steady resource of these toads.	(Elkan, 1938)
	• A toxin isolated from a dendrobatid frog (*Epipedobates tricolor*) shows promise as non-opiate pain killer and potentially derivatives used in treating Parkinson's disease and Alzheimer's.	(Salehi et al., 2018)
	• Antimicrobial peptides (AMP) from anuran skin can inhibit infection of human immune deficiency virus (HIV).	(VanCompernolle et al., 2005)
	• Skin secretions from *Phyllomedusa* frogs may be useful in treating drug-resistant infections.	(Azevedo Calderon et al., 2011)
	Indirect connections benefits	
	• Amphibian collapse in Costa Rica and Panama is associated with increased incidence of the mosquito-borne human malaria.	(Springborn et al., 2022)
	• Insights from amphibian regenerative capabilities are informing advances in regenerative medicine.	(Mahapatra et al., 2023)
Reptiles	*Direct connections benefits*	
	• The venom of *Bothrops* snakes has important antimicrobial and pharmacological properties.	(Ciscotto et al., 2009)
	• Venoms of *Heloderma* and various snake species are used in pharmaceutical drugs to treat things such as hypertension and Type 2 diabetes mellitus.	(Bordon et al., 2020)
	Indirect connections benefits	
	• The immune system of western fence lizards (*Sceloporus occidentalis*) and southern alligator lizards (*Elgaria multicarnata*) kills the pathogenic agent of Lyme disease in infected, feeding ticks.	(Lane and Quistad, 1998)

and was even used for healing superficial skin lesions (Demetrioff, 2020). The association of snakes with wisdom is also propounded through many early cultures, including Hinduism, where the god Shiva, who typically wears a snake around his neck, represents wisdom (Stanley, 2008).

Frogs, toads and salamanders

Many neotropical societies view frogs as good-luck charms or signs of fertility, dating back thousands of years (Valencia-Aguilar et al., 2013). Amazonian indigenous tribes have used skin secretions of several Dendrobatid frogs to rub on their bodies to gain power or to experience pain and euphoria (Valencia-Aguilar et al., 2013). In addition, secretions can be used in making "curare," a poison used in hunting and medicine (Valencia-Aguilar et al., 2013). In Asia, frogs and toads are associated with wisdom and magic in Chinese and Japanese cultures (DeGraaff, 1991).

Herptile biodiversity loss

Since the global herptile crisis was first recognized in the 1980s amphibian and reptile populations have declined precipitously (Rollins-Smith, 2020; Luetdke et al., 2023). Currently, 21% of the assessed reptile species and 41% of amphibian species are at risk of extinction ('IUCN Red List of Threatened Species' 2024).

Impacts of anthropogenic environmental degradation and contamination on herps

Global ecosystem changes of the Anthropocene have impacted herptiles more profoundly than any other vertebrate taxa (Barnosky et al., 2011). For amphibians, especially, their shared terrestrial and aquatic life histories, permeable skin and adaptation to species-optimal thermal, precipitation and UV radiation conditions make them a good sentinel species for environmental health and "canaries in the coalmine" for environmental degradation (Hopkins, 2007). In many areas of the globe, amphibians have been among the first taxa to show population-wide responses to genotoxic and teratogenic environmental contaminants like pesticides, herbicides, agricultural runoff, sewage, and pharmaceutical and industrial effluent (Egea-Serrano et al., 2012). Population-wide health impacts of environmental contaminants in amphibians, like atrazine, have triggered re-evaluation of legally allowed levels of chemicals in wastewater and environmental effluent to protect environmental health as well as public health (Roy, 2002). These chemicals have the potential to induce genotoxic and teratogenic changes in exposed humans as well.

Land-use change driven by human influence on the environment is a major driver of global biodiversity loss (Isbell et al., 2017). For herpetofauna specifically, habitat loss and degradation are considered crucial drivers of species declines (Ford et al., 2020). These declines will have profound implications for other organisms and ecosystems.

Impacts of climate change on herp health

Climate change is associated with warming global temperatures, changing precipitation patterns, sea level rise and increased extreme weather events. These shifts in climate are altering the habitats that amphibians and reptiles reside in, and, as such, suitable environments for their survival may be shrinking (McMenamin et al., 2008; Luetdke et al., 2023). Climatic events have been linked to local population extinctions, the predicted dispersal of herpetofauna to areas outside of their normal ranges, and projections that more herptile species will be listed as endangered, threatened or vulnerable (Olson and Saenz, 2013; Luetdke et al., 2023). In Table 2, we review the potential impacts of climate change on herptile species.

Rises in ambient temperatures may influence reptile biodiversity, especially in species with temperature-dependent sex determination because rises in temperature may skew sex ratios to levels that cannot sustain populations (Valenzuela et al., 2019); this is especially the case for chelonian diversity (Ihlow et al., 2012). It has been suggested that larval development may be the most vulnerable amphibian life stage affected by climate shifts due to more regular droughts and the general rise in water temperature in

Table 2. Summary of potential and demonstrated impacts of climate change on Herptile Health

Climate Change Category	Type of Impact	Impacts on Herptile Health	Examples of References Addressing These Impacts
Average Warming	Global average increases in temperature across all seasons	• Increased energy budgets at increased temperatures -> tradeoffs with immune function • Sex ratio biases in TSD herps • Range shrinkage • Shifts in seasonal feeding, migration, breeding • Potential for increased heat-tolerant pathogen presence • Heat avoidance behavior may lead to increased host–pathogen interactions (e.g., certain fungi) • Reduction in species richness	(Lesbarrères et al., 2014) (Biber et al., 2023) (Rollins-Smith, 2017)
Severe Precipitation Events	Drought	• Hydric stress influences immune function (can increase it in some reptiles) • Lack of rain as seasonal cue ○ Increased aestivation times, potential increased energy budgets • Range shrinkage • Shrinkage or loss of some aquatic habitats ○ Increased competition and decreased resources lead to stress ○ Increased interactions between hosts and pathogens ○ Breeding grounds disappear ○ Aquatic larvae require rapid development/plasticity to survive	(Moss et al., 2022) (Sinai et al., 2022)
	Flooding	• Novel habitat connectivity for hosts and pathogens • Increased residence time of aquatic pathogens • Water avoidance behavior may increase multi-host interactions on "islands" • Potential for habitat alteration, range shrinkage	(Walls et al., 2013)
Severe Thermal Events	Heat Waves	• Thermal stress influencing immune function • Aggregation at thermal refugia-increased host interactivity • Mortality (genetic bottleneck, population loss) • Range shrinkage in deserts, mountain tops etc • Change in disease dynamics	(Song et al., 2022) (Rollins-Smith, 2017)
	Cold Fronts	• Potential for pathogen "flare-ups" while host metabolism is low • Aggregation at thermal refugia-increased host interactivity • Mortality (genetic bottleneck, population loss, some habitats may become inhospitable) • Breeding or development interruption	(Rollins-Smith, 2017)
Increased Storm Intensities	Habitat Alteration: Lightning: Fire Frequencies	• Range shrinkage or expansion: habitat structural change leads to changes in refugia, resources • pH changes in habitat influence host and pathogen	(Hossack and Pilliod, 2011)
	Habitat Alteration: Wind Damage: Canopy destruction	• Range shrinkage or expansion: habitat structural change leads to changes in refugia, resources • Potential for increased UV exposure with canopy loss-influence both pathogens and microbiome at forest floors	(Marroquín-Páramo et al., 2021)
	Habitat Alteration: Storm Surge: Saltwater Inundation	• Ecosystem change based on salt-tolerant species (host, pathogen, environment) • Hydric stress influencing immune function • Mass mortality events, range shrinkage, population extinction expected for amphibians	(Albecker and McCoy, 2017)

amphibian breeding habitats (Sinai et al., 2022). Climate change (i.e., high temperatures and increased drought in some regions) may be beneficial or harmful to herptile species in terms of changing pathogen dynamics, pathogen pollution by invasive species, water stress and trophic mismatch.

Pathogen dynamics

The herptile host–pathogen relationship is highly temperature-dependent and likely one of the most significant drivers determining infectious disease outcomes (Rohr et al., 2008). Higher temperatures, in both live animal exposure experiments and wild populations, are associated with increased disease occurrence and severity (Price et al., 2019). It has been hypothesized that increased drought will reduce the prevalence of the amphibian skin-eating fungus, *Batrachochytrium dendrobatidis* (*Bd*), because the pathogen is dependent on freshwater for reproduction and survival (Fisher et al., 2009). Others argue that *Bd* is amplified by drought conditions (Pounds et al., 1999) because infection of the pelvic patch, important for rehydration, would make frogs more vulnerable during dry periods. For reptiles, seasonal climate variations that alter overwintering conditions and ambient air temperatures, likely play a crucial role in pathogen transmission and disease culmination, which has been suggested for snake fungal disease (Albecker and McCoy, 2017). In another reptile study, warmer temperatures resulted in overall higher ectoparasite infections in wild common lizard (*Zootoca vivipara*) females, though the lizard's color variety/morphotype varied the rate of infection (Wu et al., 2022). The degree to which climate alterations affect disease outcomes of individual pathogen-exposed

https://doi.org/10.1017/one.2024.14 Published online by Cambridge University Press

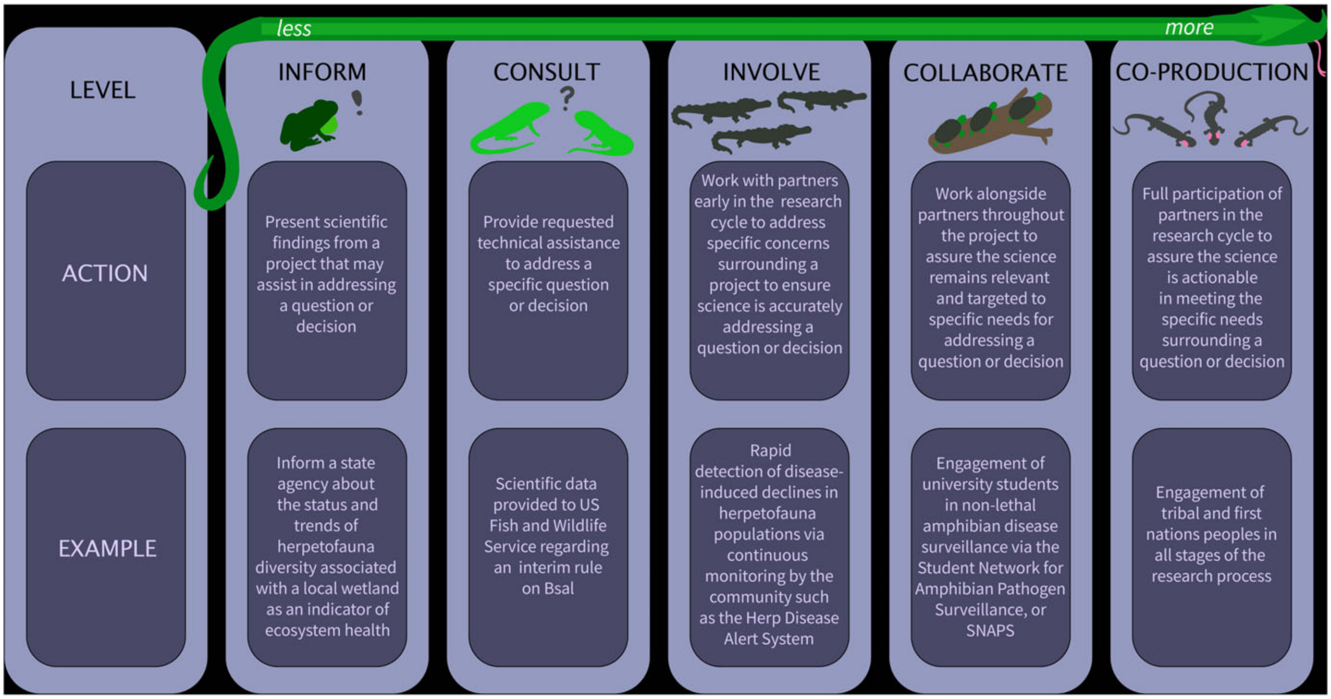

Figure 1. Examples of how Citizen Science can be incorporated into herptile One Health approaches. Adapted from https://www.usgs.gov/media/images/illustration-participatory-science-usgs-ecosystems-mission-area.

amphibians and reptiles and how this translates to a landscape scale and/or population level, still needs to be further elucidated.

Hydric stress

While many reptiles are adapted to arid and mesic environments with limited water availability, hydric stress can influence thermoregulatory behavior (Ladyman and Bradshaw, 2003), influence sex ratios in offspring (Dupoué et al., 2019) and stagnate reproduction (Dezetter et al., 2021). These scenarios can often lead to reproductive failure and decreases in recruitment (Chandler et al., 2017). All amphibians rely on availability of freshwater or moisture for reproduction regardless of life history. Because most amphibians display a biphasic life history, eggs, tadpoles and metamorphs are particularly vulnerable to the direct effects of drought such as mortality from desiccation or dehydration (Li et al., 2013). Somewhat counterintuitively, reptiles under hydric stress show enhanced components of immune function (Brusch et al., 2020), which may be a result of adaptation to arid environments, or to counteract the reduced immune capacity of reptiles maintaining lower body temperatures when under hydric stress (Ladyman and Bradshaw, 2003). This phenomenon deserves further study to investigate how it may influence host–pathogen dynamics.

Trophic mismatches

Changes in phenology of herpetofauna food sources could result in trophic mismatches upon spring emergence (Kharouba et al., 2018), unless phenology shifts in herpetofauna are synchronous with shifts in their food sources. Conversely, winters are predicted to be shorter in some parts of the globe (Räisänen et al., 2004), which could be beneficial for reptiles and amphibians that hibernate, as long as food sources are available. Experimental work suggested that a shorter, warmer winter was beneficial for survival and body mass changes during hibernation for common toads (*Bufo bufo*) (Üveges et al., 2016). Alternatively, climate change may result in prolonged estivation or behavioral refugia time which could lead to reduced foraging or breeding windows and ultimately population declines (Sinervo et al., 2010).

Herptile diseases

For herpetofauna, negative effects on biodiversity are most notable when looking at declines caused by the global spread of emerging infectious diseases. One of the best cases exemplifying the disastrous results of species loss is frog population collapse due to *Bd* that led to declines in snake species, key amphibian predators (Zipkin and DiRenzo, 2022). In addition to over 500 amphibian species declines, at least ninety amphibian species are believed to have gone extinct because of this fungal panzootic (Scheele et al., 2019). In Panama, a comparison of pre- and post- *Bd* epizootic Neotropical snake species richness showed a 20% decline following a 75% decline in amphibian abundance (Zipkin et al., 2020). Increases in human malaria cases have been associated with the decline of amphibian mosquito predators (Springborn et al., 2022). Overall, reptile and amphibian declines can be attributed to two overarching mechanisms: mortality and decreased recruitment. Unregulated global trade has introduced deadly pathogens, like chytrid (*Bd* and *B. salamandrivorans*, *Bsal*) fungi, *Ophidiomyces ophiodiicola* (i.e., causative agent of snake fungal disease) and ranaviruses, to immunologically naive herptile populations resulting in unchecked spread through native populations.

Inclusion of herps in the One Health Joint Plan of Action

The One Health Joint Plan of Action (OH JPA 2022-2026) developed by the Quadripartite Organizations (FAO, UNEP, WOAH, WHO) – includes six action tracks with the last one

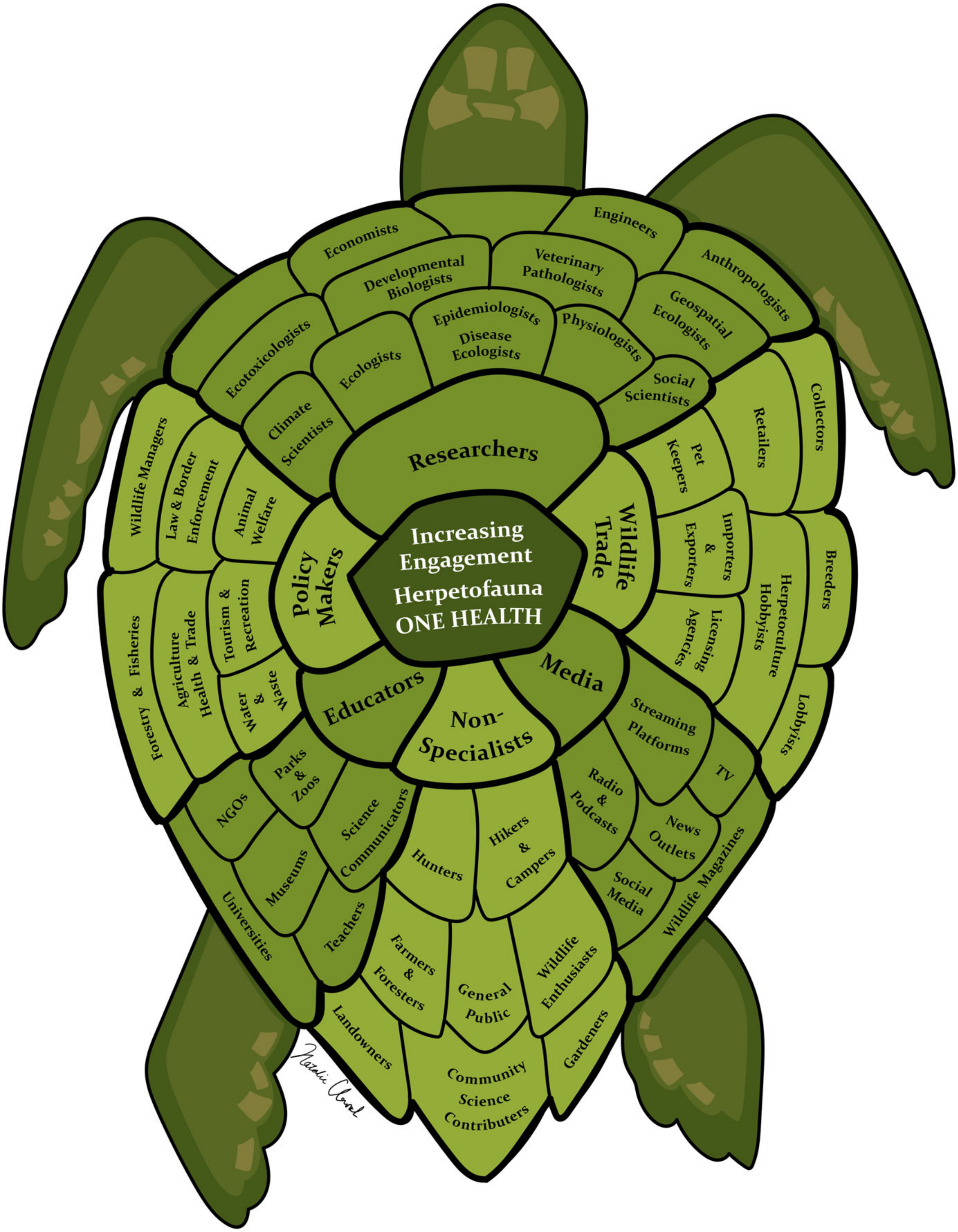

Figure 2. Visual schematic representing the diverse stakeholders that can contribute to a successful One Health approach for herpetofauna. Credit: Natalie Claunch.

https://doi.org/10.1017/one.2024.14 Published online by Cambridge University Press

focused on integrating the environment into One Health *(Protect and restore biodiversity, prevent the degradation of ecosystems and the wider environment to jointly support the health of people, animals, plants and ecosystems, underpinning sustainable development).* The biodiversity and health of herptile species, aligned with ecosystem health, has direct and indirect consequences for plant, animal and human health. The health of these ectotherms, which are sensitive to environmental change, needs to be added to the mainstream One Health approach (see the OH JPA 2022-2026, Action 6.2).

Developing a holistic approach to manage emerging herp threats

To apply a true "One Health" approach, we must expand our thinking beyond pathogens/diseases of concern and include overall health and determinants of health for monitoring and conservation actions. For example, the approach taken by Wittrock et al. (2019) that considers a "Determinants of Health" model for caribou and sockeye salmon. This model, which has roots in public health, considers biotic, abiotic and social contributions that factor into health outcomes (Wittrock et al., 2019). Can we foresee something similar for amphibians and reptiles, to broaden our approach to managing health with a holistic, systems-based approach? How do we accomplish this with limited resources dedicated to herpetofauna? Are there existing systems already in place that can be utilized? The following are a few selected examples that might be included in One Health approaches.

Engaging participatory science into herp monitoring programs

OH JPA Activity 6.3.8 - Engage with citizen science on data collection for monitoring the health of the environment to inform action.

It is widely accepted that in an environment where professional resources for species monitoring are increasingly scarce, community scientists are of greater importance. Despite concerns about the robustness of data collected in this way and the biosecurity practices employed, participatory science is making a significant contribution in many regions (Schmeller et al., 2009). Perhaps, increasing the engagement of the public may prove useful, raising awareness of the plight of herpetofauna and giving the public a role in herpetofauna health and conservation, ultimately elevating the popularity status of herpetofauna despite their cryptic nature (e.g., see Figure 1).

Engaging the IUCN for protecting and restoring biodiversity of herpetofauna

Currently, the International Union for Conservation of Nature (IUCN) is composed of a number of working groups, including the Amphibian Specialist Group (ASG), the Snake Specialist Group (SSG), the Tortoise and Freshwater Turtle Specialist group (TFTSG), Marine Turtle Specialist Group (MTSG) and the Crocodile Specialist Group (CSG) where government officials, researchers and workers across sectors at the local, national, regional and global levels review threats and implement conservation action plans. These include developing shared databases and surveillance across different sectors and identifying new solutions that address the root causes and links between risk factors and impacts to biodiversity. Using the WHO model, the ASG and SSG could implement a One Health approach to integrate research along the amphibian, reptile, human, animal, plant and environmental health interface. This integrated framework would identify and promote multi-sectoral approaches to reduce health threats, including the transformations required to prevent and mitigate the impact of current and future health challenges at regional, country and global levels (Cunningham et al., 2017). Such an approach could be combined with task forces already in place (e.g., Bsal Task Force, https://www.salamanderfungus.org/; https://sosanfibios.org/) to make recommendations for research on emerging disease threats and develop long-term global plans of action to avert outbreaks. The panel could additionally have a role in investigating the impact of human activity on the environment and wildlife habitats, and how this drives disease threats.

CALL TO ACTION: Integrating herps into a One Health approach

Integrating herps into the One Health approach would potentially have multiple beneficial impacts on public health and well-being. Herein, we implore a call to action for those using a One Health approach to integrate reptiles and amphibians, indicators of ecosystem health, into their decision-making. The One Health approach requires interdisciplinary collaboration to promote a sustainable future for humans, animals, plants and their shared ecosystems (One Health High-Level Expert Panel (OHHLEP) et al. 2022) and is being implemented in the One Health Joint Plan of Action. Unfortunately, we often limit our view of One Health to a few closely related disciplines and neglect the broader scope of factors that may be equally significant. A One Health team must engage representatives and stakeholders across multiple sectors to coordinate and collaborate for an effective, holistic response (Figure 2). This need for a holistic response is included in the One Health Joint Plan of Action, emphasizing the importance of incorporating the environment sector in One Health approaches (e.g., see OH JPA 2022-2026, Action 6.4.4).

One Health should be our lifestyle, ingrained in our day-to-day activities, abandoning our consumerism for the sake of nature and, hence, our well-being. Can we change the way we currently live? Is public engagement the answer (the glue) to imploring decision makers and high-level committees to consider herpetofauna in One Health approaches? Indeed, to achieve health for all life we need a global community working united.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

Acknowledgments. We acknowledge the first Global Amphibian and Reptile Disease (GARD) conference organizers for providing the opportunity and venue for the in-person meeting of this author group that laid the foundation for crafting this manuscript to share with the scientific and broader communities. We also thank two USGS scientists who provided excellent critiques on an earlier version of this manuscript. NC was supported by National Science Foundation Postdoctoral Research Fellowships in Biology Program under Grant No. 2109663. We would like to take this opportunity to also acknowledge the First Nations who have used a One Health approach for millennia. We honor their histories, languages and cultures that reflect how they cared for the land and species discussed in this article.

Author contributions. Camille Hopkins: Conceptualization, literature search, writing, editing, tables

David Lesbarrères: Conceptualization, literature search, writing, editing, tables

Natalie Claunch: Conceptualization, literature search, writing, figure

Eveline Emmenegger: Conceptualization, literature search, writing, editing, tables

Bennett Hardy: Conceptualization, literature search, writing

María Torres-Sánchez: Conceptualization, literature search, writing

Tariq Stark: Literature searching, writing, editing

Angela Julian: Conceptualization, literature search, writing, editing, tables

Sarah McGrath-Blaser: Conceptualization, literature search, writing

Christine Parker-Graham: Conceptualization, literature search, writing

Katie Haman: Conceptualization, literature search, writing

Ashley Morgan: Editing, literature search

Debra L. Miller: Conceptualization, literature search, writing, editing, tables.

Funding statement. This project received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interests. The authors have no conflicts of interest to declare.

Ethics statement. Ethical approval and consent are not relevant to this article type.

Connections references

Stephen C (2023) How do the practical and pragmatic limitations in the design or implementation of wildlife disease surveillance systems bias our understanding of the drivers, epidemiology and impact of pathogen traffic between wildlife and people or domestic species, or within wildlife host populations? *Research Directions: One Health.* **1**, e4, 1. https://doi.org/10.1017/one.2022.5.

References

Adams MJ and Muths E (2019) Conservation research across scales in a national program: how to be relevant to local management yet general at the same time. *Biological Conservation* **236**, 100–106. https://doi.org/10.1016/j.biocon.2019.05.027.

Albecker MA and McCoy MW (2017) Adaptive responses to salinity stress across multiple life stages in anuran amphibians. *Frontiers in Zoology* **14**(1), 40. https://doi.org/10.1186/s12983-017-0222-0.

Attademo AM, Peltzer PM and Lajmanovich RC (2005) Amphibians occurring in soybean and implications for biological control in Argentina. *Agriculture, Ecosystems & Environment* **106**(4), 389–394. https://doi.org/10.1016/j.agee.2004.08.012.

Azevedo Calderon LD, Silva ADAE, Ciancaglini P and Stábeli RG (2011) Antimicrobial peptides from *Phyllomedusa* frogs: from biomolecular diversity to potential nanotechnologic medical applications. *Amino Acids* **40**(1), 29–49. https://doi.org/10.1007/s00726-010-0622-3.

Barnosky AD, Matzke N, Tomiya S, Wogan GOU, Swartz B, Quental TB, Marshall C, McGuire JL, Lindsey EL, Maguire KC, Mersey B and Ferrer EA (2011) Has the Earth's sixth mass extinction already arrived? *Nature* **471**(7336), 51–57. https://doi.org/10.1038/nature09678.

Biber MF, Voskamp A and Hof C (2023) Potential effects of future climate change on global reptile distributions and diversity. *Global Ecology and Biogeography* **32**(4), 519–534. https://doi.org/10.1111/geb.13646.

Bordon KDCF, Cologna CT, Fornari-Baldo EC, Pinheiro-Júnior EL, Cerni FA, Amorim FG, Anjolette FAP, Cordeiro FA, Wiezel GA, Cardoso IA, Ferreira IG, Oliveira ISD, Boldrini-França J, Pucca MB, Baldo MA and Arantes EC (2020) From animal poisons and venoms to medicines: achievements, challenges and perspectives in drug discovery. *Frontiers in Pharmacology.* **11**, 1132. https://doi.org/10.3389/fphar.2020.01132.

Brusch GA, Mills AM, Walman RM, Masuda G, Byeon A, DeNardo DF and Stahlschmidt ZR (2020) Dehydration enhances cellular and humoral immunity in a mesic snake community. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology* **333**(5), 306–315. https://doi.org/10.1002/jez.2358.

Celedón-Neghme C, San Martin LA, Victoriano PF and Cavieres LA (2008) Legitimate seed dispersal by lizards in an alpine habitat: the case of *Berberis empetrifolia* (Berberidaceae) dispersed by *Liolaemus belii* (Tropiduridae). *Acta Oecologica* **33**(3), 265–271. https://doi.org/10.1016/j.actao.2007.11.006.

Chandler HC, McLaughlin DL, Gorman TA, McGuire KJ, Feaga JB and Haas CA (2017) Drying rates of ephemeral wetlands: implications for breeding amphibians. *Wetlands* **37**(3), 545–557. https://doi.org/10.1007/s13157-017-0889-1.

Ciscotto P, Machado De Avila RA, Coelho EAF, Oliveira J, Diniz CG, Farías LM, De Carvalho MAR, Maria WS, Sanchez EF, Borges A and Chávez-Olórtegui C (2009) Antigenic, microbicidal and antiparasitic properties of an l-amino acid oxidase isolated from *Bothrops jararaca* snake venom. *Toxicon* **53**(3), 330–341. https://doi.org/10.1016/j.toxicon.2008.12.004.

Crump M (2024) *Eye of Newt and Toe of Frog, Adder's Fork and Lizard's Leg: The Lore and Mythology of Amphibians and Reptiles.* Chicago, IL: University of Chicago Press. https://press.uchicago.edu/ucp/books/book/chicago/E/bo17338714.html (accessed 14 May 2024).

Cunningham AA, Daszak P and Wood JLN (2017) One Health, emerging infectious diseases and wildlife: two decades of progress? *Philosophical Transactions of the Royal Society B: Biological Sciences* **372**(1725), 20160167. https://doi.org/10.1098/rstb.2016.0167.

de-Oliveira-Nogueira CH, Souza UF, Machado TM, Figueiredo-de-Andrade CA, Mônico AT, Sazima I, Sazima M and Toledo LF (2023) Between fruits, flowers and nectar: the extraordinary diet of the frog *Xenohyla truncata*. *Food Webs.* **35**, e00281. https://doi.org/10.1016/j.fooweb.2023.e00281.

DeGraaff RM (1991) *Rate this Book The Book of the Toad: A Natural and Magical History of Toad-Human Relations.* Rochester, Vermont USA: Park Street Press (accessed 15 February 2024).

Demetrioff J (2020) Ambiguous snake manipulations: the 'powers' and entity of health in antiquity. *Electra.* Available at https://www.academia.edu/62656149/Ambiguous_Snake_Manipulations_The_Powers_and_Entity_of_Health_in_Antiquity (accessed 14 May 2024).

Dezetter M, Le Galliard JF, Guiller G, Guillon M, Leroux-Coyau M, Meylan S, Brischoux F, Angelier F and Lourdais O (2021) Water deprivation compromises maternal physiology and reproductive success in a cold and wet adapted snake *Vipera berus*. *Conservation Physiology* **9**(1), coab071. https://doi.org/10.1093/conphys/coab071.

Dupoué A, Lourdais O, Meylan S, Brischoux F, Angelier F, Rozen-Rechels D, Marcangeli Y, Decencière B, Agostini S and Le Galliard J (2019) Some like it dry: water restriction overrides heterogametic sex determination in two reptiles. *Ecology and Evolution* **9**(11), 6524–6533. https://doi.org/10.1002/ece3.5229.

Egea-Serrano A, Relyea RA, Tejedo M and Torralva M (2012) Understanding of the impact of chemicals on amphibians: a meta-analytic review. *Ecology and Evolution* **2**(7), 1382–1397. https://doi.org/10.1002/ece3.249.

Elkan ER (1938) The Xenopus pregnancy test. *British Medical Journal* **2**(4067), 1253–1274. https://doi.org/10.1136/bmj.2.4067.1253.

Fisher MC, Garner TWJ and Walker SF (2009) Global emergence of *Batrachochytrium dendrobatidis* and amphibian chytridiomycosis in space, time, and host. *Annual Review of Microbiology* **63**(1), 291–310. https://doi.org/10.1146/annurev.micro.091208.073435.

Ford J, Hunt DAGA, Haines GE, Lewis M, Lewis Y and Green DM (2020) Adrift on a sea of troubles: can amphibians survive in a human-dominated world? *Herpetologica* **76**(2), 251. https://doi.org/10.1655/0018-0831-76.2.251.

Gibbons JW, Winne CT, Scott DE, Willson JD, Glaudas X, Andrews KM, Todd BD, Fedewa LA, Wilkinson L, Tsaliagos RN, Harper SJ, Greene JL, Tuberville TD, Metts BS, Dorcas ME, Nestor JP, Young CA, Akre T, Reed RN, Buhlmann KA, Norman J, Croshaw DA, Hagen C and Rothermel BB (2006) Remarkable amphibian biomass and abundance in an isolated wetland: implications for wetland conservation. *Conservation Biology* **20**(5), 1457–1465. https://doi.org/10.1111/j.1523-1739.2006.00443.x.

Hocking DJ and Babbitt KJ (2014) Amphibian contributions to ecosystem services. *Herpetological Conservation and Biology* **9**(1), 1–17.

Hopkins WA (2007) Amphibians as models for studying environmental change. *ILAR Journal* **48**(3), 270–277. https://doi.org/10.1093/ilar.48.3.270.

Hossack BR and Pilliod DS (2011) Amphibian responses to wildfire in the western united states: emerging patterns from short-term studies. *Fire Ecology* **7**(2), 129–144. https://doi.org/10.4996/fireecology.0702129.

Ihlow F, Dambach J, Engler JO, Flecks M, Hartmann T, Nekum S, Rajaei H and Rödder D (2012) On the brink of extinction? How climate change may affect global chelonian species richness and distribution. *Global Change Biology* **18**(5), 1520–1530. https://doi.org/10.1111/j.1365-2486.2011.02623.x.

Isbell F, Gonzalez A, Loreau M, Cowles J, Díaz S, Hector A, Mace GM, Wardle DA, O'Connor MI, Duffy JE, Turnbull LA, Thompson PL and Larigauderie A (2017) Linking the influence and dependence of people on biodiversity across scales. *Nature* **546**(7656), 65–72. https://doi.org/10.1038/nature22899.

IUCN Red List of Threatened Species (2024) https://www.iucnredlist.org/en (accessed 14 May 2024).

Jacobson S and Lopez AF (1994) Biological impacts of ecotourism - tourists and nesting turtles in Tortuguero National Park, Costa Rica. *Wildlife Society Bulletin* **22**, 414–419.

Jeon JY, Lee DK and Kim JH (2023) Functional group analyses of herpetofauna in South Korea using a large dataset. *Scientific Data* **10**(1), 15. https://doi.org/10.1038/s41597-022-01924-z.

Kharouba HM, Ehrlén J, Gelman A, Bolmgren K, Allen JM, Travers SE and Wolkovich EM (2018) Global shifts in the phenological synchrony of species interactions over recent decades. *Proceedings of The National Academy of Sciences of The United States of America* **115**(20), 5211–5216. https://doi.org/10.1073/pnas.1714511115.

Ladyman M and Bradshaw D (2003) The influence of dehydration on the thermal preferences of the Western tiger snake, *Notechis scutatus*. *Journal of Comparative Physiology B* **173**(3), 239–246. https://doi.org/10.1007/s00360-003-0328-x.

Lane RS and Quistad GB (1998) Borreliacidal factor in the blood of the western fence lizard (*Sceloporus occidentalis*). *The Journal of Parasitology* **84**(1), 29. https://doi.org/10.2307/3284524.

Lazarou A (2018) Golden gorgon-medousa artwork in ancient hellenic world, Available at https://doi.org/10.5281/ZENODO.1451898.

Lesbarrères D, Ashpole SL, Bishop CA, Blouin-Demers G, Brooks RJ, Echaubard P, Govindarajulu P, Green DM, Hecnar SJ, Herman T, Houlahan J, Litzgus JD, Mazerolle MJ, Paszkowski CA, Rutherford P, Schock DM, Storey KB and Lougheed SC (2014) Conservation of herpetofauna in northern landscapes: threats and challenges from a Canadian perspective. *Biological Conservation* **170**, 48–55. https://doi.org/10.1016/j.biocon.2013.12.030.

Li C, Xie F, Che J and Jiang J (2017) Monitoring and research of amphibians and reptiles diversity in key areas of China. *Biodiversity Science* **25**(3), 246–254. https://doi.org/10.17520/biods.2016137.

Li Y, Cohen JM and Rohr JR (2013) Review and synthesis of the effects of climate change on amphibians. *Integrative Zoology* **8**(2), 145–161. https://doi.org/10.1111/1749-4877.12001.

Luedtke JA, Chanson J, Neam K, Hobin L, Maciel AO, *et al.* (2023) Ongoing declines for the world's amphibians in the face of emerging threats. *Nature* **622**(7982), 308–314. https://doi.org/10.1038/s41586-023-06578-4.

Mahapatra C, Naik P, Swain SK and Mohapatra PP (2023) Unravelling the limb regeneration mechanisms of *Polypedates maculatus*, a sub-tropical frog, by transcriptomics. *BMC Genomics* **24**(1), 122. https://doi.org/10.1186/s12864-023-09205-8.

Marroquín-Páramo JA, Suazo-Ortuño I, Urbina-Cardona N and Benítez-Malvido J (2021) Cumulative effects of high intensity hurricanes on herpetofaunal assemblages along a tropical dry forest chronosequence. *Forest Ecology and Management.* **479**, 118505. https://doi.org/10.1016/j.foreco.2020.118505.

McMenamin SK, Hadly EA and Wright CK (2008) Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. *Proceedings of The National Academy of Sciences of The United States of America* **105**(44), 16988–16993. https://doi.org/10.1073/pnas.0809090105.

Morrison BJ and Rubin JE (2020) Detection of multidrug-resistant Gram-negative bacteria from imported reptile and amphibian meats. *Journal of Applied Microbiology* **129**(4), 1053–1061. https://doi.org/10.1111/jam.14658.

Moss WE, Harper LR, Davis MA, Goldberg CS, Smith MM and Johnson PTJ (2022) Navigating the trade-offs between environmental DNA and conventional field surveys for improved amphibian monitoring. *Ecosphere* **13**(2), e3941. https://doi.org/10.1002/ecs2.3941.

Olson DH and Saenz D (2013) *Amphibians and Climate Change.* US Department of Agriculture, Forest Service, Climate Change Resource Center.

One Health High-Level Expert Panel (OHHLEP),Adisasmito W B, Almuhairi S, Behravesh C B, Bilivogui Pépé, Bukachi S A, Casas N, Cediel Becerra N, Charron D F, Chaudhary A, Ciacci Zanella J R, Cunningham A A, Dar O, Debnath N, Dungu B, Farag E, Gao G F, Hayman D T S, Khaitsa M, Koopmans M P G, Machalaba C, Mackenzie J S, Markotter W, Mettenleiter T C, Morand S, Smolenskiy V, Zhou L, Dvorin J D (2022) One Health: a new definition for a sustainable and healthy future. *PLOS Pathogens* **18**(6), e1010537. https://doi.org/10.1371/journal.ppat.1010537.

Pearce RJ (2005) Turtles from Turtle Island: an archaeological perspective from Iroquoia. *Ontario Archaeology* **79/80**. Available at https://www.academia.edu/10651330/Turtles_from_Turtle_Island_An_Archaeological_Perspective_from_Iroquoia accessed 14 May 2024.

Pounds JA, Fogden MPL and Campbell JH (1999) Biological response to climate change on a tropical mountain. *Nature* **398**(6728), 611–615. https://doi.org/10.1038/19297.

Price SJ, Leung WTM, Owen CJ, Puschendorf R, Sergeant C, Cunningham AA, Balloux F, Garner TWJ and Nichols RA (2019) Effects of historic and projected climate change on the range and impacts of an emerging wildlife disease. *Global Change Biology* **25**(8), 2648–2660. https://doi.org/10.1111/gcb.14651.

Räisänen J, Hansson U, Ullerstig A, Döscher R, Graham LP, Jones C, Meier HEM, Samuelsson P and Willén U (2004) European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Climate Dynamics* **22**(1), 13–31. https://doi.org/10.1007/s00382-003-0365-x.

Rohr JR, Raffel TR, Romansic JM, McCallum H and Hudson PJ (2008) Evaluating the links between climate, disease spread, and amphibian declines. *Proceedings of The National Academy of Sciences of The United States of America* **105**(45), 17436–17441. https://doi.org/10.1073/pnas.0806368105.

Rollins-Smith LA (2017) Amphibian immunity-stress, disease, and climate change. *Developmental & Comparative Immunology* **66**, 111–119. https://doi.org/10.1016/j.dci.2016.07.002.

Rollins-Smith LA (2020) Global amphibian declines, disease, and the ongoing battle between *Batrachochytrium* fungi and the immune system. *Herpetologica* **76**(2), 178. https://doi.org/10.1655/0018-0831-76.2.178.

Roy D (2002) Amphibians as environmental sentinels. *Journal of Biosciences* **27**(3), 187–188. https://doi.org/10.1007/BF02704906.

Salehi B, Sestito S, Rapposelli S, Peron G, Calina D, Sharifi-Rad M, Sharopov F, Martins N and Sharifi-Rad J (2018) Epibatidine: a promising natural alkaloid in health. *Biomolecules* **9**(1), 6. https://doi.org/10.3390/biom9010006.

Scheele BC, Pasmans F, Skerratt LF, Berger L, Martel A, Beukema W, Acevedo AA, Burrowes PA, Carvalho T, Catenazzi A, De La Riva I, Fisher MC, Flechas SV, Foster CN, Frías-Álvarez P, Garner TWJ, Gratwicke B, Guayasamin JM, Hirschfeld M, Kolby JE, Kosch TA, La Marca E, Lindenmayer DB, Lips KR, Longo AV, Maneyro R, McDonald CA, Mendelson J, Palacios-Rodriguez P, Parra-Olea G, Richards-Zawacki CL, Rödel M-O, Rovito SM, Soto-Azat C, Toledo LF, Voyles J, Weldon C, Whitfield SM, Wilkinson M, Zamudio KR and Canessa S (2019) Amphibian fungal panzootic causes catastrophic and ongoing loss of biodiversity. *Science* **363**(6434), 1459–1463. https://doi.org/10.1126/science.aav0379.

Schmeller DS, Henry P, Julliard R, Gruber B, Clobert J, Dziock F, Lengyel S, Nowicki P, Déri E, Budrys E, Kull T, Tali K, Bauch B, Settele J, Van Swaay C, Kobler A, Babij V, Papastergiadou E and Henle K (2009) Advantages of volunteer-based biodiversity monitoring in Europe. *Conservation Biology* **23**(2), 307–316. https://doi.org/10.1111/j.1523-1739.2008.01125.x.

Seale DB (1980) Influence of amphibian larvae on primary production, nutrient flux, and competition in a pond ecosystem. *Ecology* **61**(6), 1531–1550. https://doi.org/10.2307/1939059.

Semlitsch RD, O.'Donnell KM and Thompson FR (2014) Abundance, biomass production, nutrient content, and the possible role of terrestrial salamanders in Missouri Ozark forest ecosystems. *Canadian Journal of Zoology* **92**(12), 997–1004. https://doi.org/10.1139/cjz-2014-0141.

Sinai N, Glos J, Mohan AV, Lyra ML, Riepe M, Thöle E, Zummach C and Ruthsatz K (2022) Developmental plasticity in amphibian larvae across the world: investigating the roles of temperature and latitude. *Journal of Thermal Biology*. **106**, 103233. https://doi.org/10.1016/j.jtherbio.2022.103233.

Sinervo B, Méndez-de-la-Cruz F, Miles DB, Heulin B, Bastiaans E, Villagrán-Santa Cruz M, Lara-Resendiz R, Martínez-Méndez N, Calderón-Espinosa ML, Meza-Lázaro RN, Gadsden H, Avila LJ, Morando M, De La Riva IJ, Sepulveda PV, Rocha CFD, Ibargüengoytía N, Puntriano CA, Massot M, Lepetz V, Oksanen TA, Chapple DG, Bauer AM, Branch WR, Clobert J and Sites JW (2010) Erosion of lizard diversity by climate change and altered thermal niches. *Science* **328**(5980), 894–899. https://doi.org/10.1126/science.1184695.

Song U, Yang E, Kim MW, Kim B, Kwak S, Oh S and Hong M (2022) Predicting the effects of climate change on tadpole stage fitness in the Korean brown frog, *Rana uenoi*, (Amphibia: Ranidae). *Matsui, Asian Journal of Conservation Biology* **11**(1), 41–48, 2014.

Springborn MR, Weill JA, Lips KR, Ibáñez R and Ghosh A (2022) Amphibian collapses increased malaria incidence in Central America. *Environmental Research Letters* **17**(10), 104012. https://doi.org/10.1088/1748-9326/ac8e1d.

Stanley J (2008) Snakes: objects of religion, fear, and myth. *Journal of Integrative Biology* **2**, 42–58.

Taçon PSC (2008) Rainbow colour and power among the Waanyi of Northwest Queensland. *Cambridge Archaeological Journal* **18**(2), 163–176. https://doi.org/10.1017/S0959774308000231.

THE 17 GOALS | Sustainable Development (2024), https://sdgs.un.org/goals, (accessed 11 April 2024).

Üveges B, Mahr K, Szederkényi M, Bókony V, Hoi H and Hettyey A (2016) Experimental evidence for beneficial effects of projected climate change on hibernating amphibians. *Scientific Reports* **6**(1), 26754. https://doi.org/10.1038/srep26754.

Valencia-Aguilar A, Cortés-Gómez AM and Ruiz-Agudelo CA (2013) Ecosystem services provided by amphibians and reptiles in Neotropical ecosystems. *International Journal of Biodiversity Science, Ecosystem Services & Management* **9**(3), 257–272. https://doi.org/10.1080/21513732.2013.821168.

Valenzuela N, Literman R, Neuwald JL, Mizoguchi B, Iverson JB, Riley JL and Litzgus JD (2019) Extreme thermal fluctuations from climate change unexpectedly accelerate demographic collapse of vertebrates with temperature-dependent sex determination. *Scientific Reports* **9**(1), 4254. https://doi.org/10.1038/s41598-019-40597-4.

VanCompernolle SE, Taylor RJ, Oswald-Richter K, Jiang J, Youree BE, Bowie JH, Tyler MJ, Conlon JM, Wade D, Aiken C, Dermody TS, KewalRamani VN, Rollins-Smith LA and Unutmaz D (2005) Antimicrobial peptides from amphibian skin potently inhibit human immunodeficiency virus infection and transfer of virus from dendritic cells to T cells. *Journal of Virology* **79**(18), 11598–11606. https://doi.org/10.1128/JVI.79.18.11598-11606.2005.

Vittecoq M, Godreuil S, Prugnolle F, Durand P, Brazier L, Renaud N, Arnal A, Aberkane S, Jean-Pierre H, Gauthier-Clerc M, Thomas F and Renaud F (2016) Antimicrobial resistance in wildlife. *Journal of Applied Ecology* **53**(2), 519–529. https://doi.org/10.1111/1365-2664.12596.

Walls S, Barichivich W and Brown M (2013) Drought, deluge and declines: the impact of precipitation extremes on amphibians in a changing climate. *Biology* **2**(1), 399–418. https://doi.org/10.3390/biology2010399.

Wittrock J, Duncan C and Craig S (2019) A determinants of health conceptual model for fish and wildlife health. *Journal of Wildlife Diseases* **55**(2), 285. https://doi.org/10.7589/2018-05-118.

Wu Q, Miles DB, Richard M, Rutschmann A and Clobert J (2022) Intraspecific diversity alters the relationship between climate change and parasitism in a polymorphic ectotherm. *Global Change Biology* **28**(4), 1301–1314. https://doi.org/10.1111/gcb.16018.

Zipkin EF and DiRenzo GV (2022) Biodiversity is decimated by the cascading effects of the amphibian-killing chytrid fungus. *PLOS Pathogens* **18**(7), e1010624. https://doi.org/10.1371/journal.ppat.1010624.

Zipkin EF, DiRenzo GV, Ray JM, Rossman S and Lips KR (2020) Tropical snake diversity collapses after widespread amphibian loss. *Science* **367**(6479), 814–816. https://doi.org/10.1126/science.aay5733.