Balancing the Scales: Including Under-represented Herptile Species in a One Health Approach

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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.

1- 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.

2- 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) ('THE 17 GOALS | Sustainable Development' 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.

2a- Herps and Plant Health

Amphibians and reptiles contribute to overall plant health through seed dispersal and pollination and as predators of crop pests (Hocking and Babbitt 2014; Valencia-Aguilar *et al.* 2013). 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).

2b- 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).

2c- 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).

3- 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 longissimu*s), which derives its name from this god, was allowed to roam freely in 'healing temples' in ancient Greece 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).

4-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).

4a- 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.

4b- 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 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 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).

5- 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.

6- 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 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).

6a- 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 (for example see Fig. 1).

7- 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 World Health Organization 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.

8- 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 wellbeing. 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.

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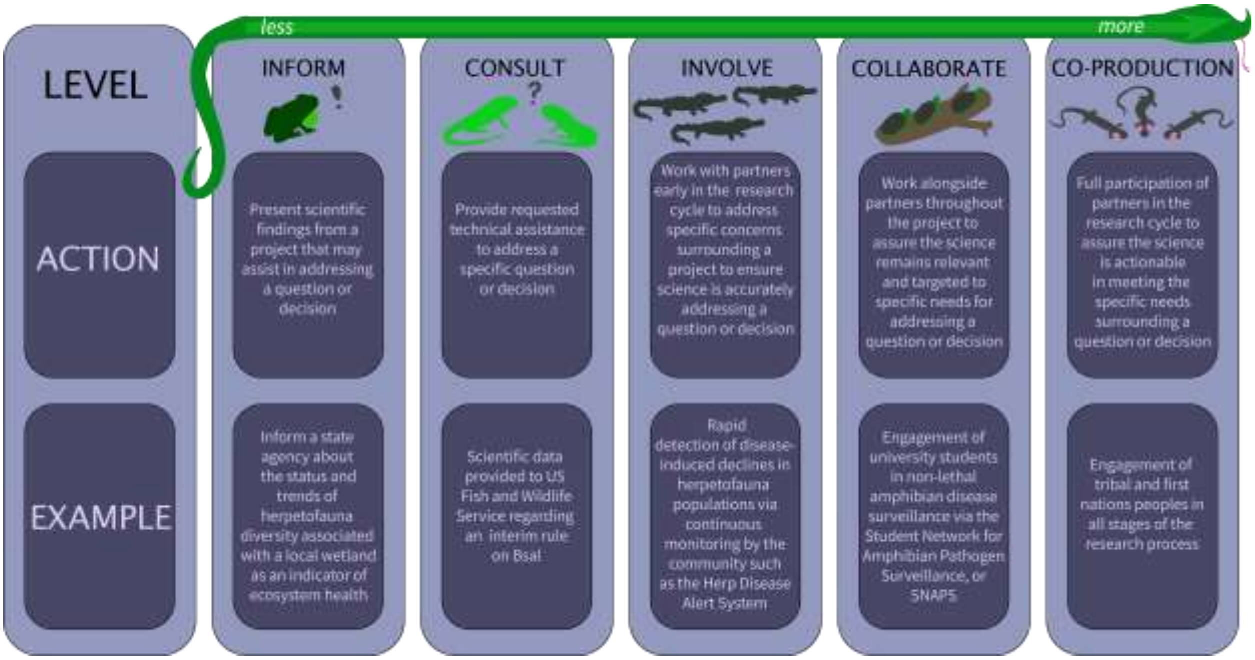

LEVEL	INFORM	CONSULT	INVOLVE	COLLABORATE	CO-PRODUCTION
ACTION	Present scientific findings from a project that may assist in addressing a question or decision	Provide requested technical assistance to address a specific question or decision	Work with partners early in the research cycle to address specific concerns surrounding a project to ensure science is accurately addressing a question or decision	Work alongside partners throughout the project to assure the science remains relevant and targeted to specific needs for addressing a question or decision	Full participation of partners in the research cycle to assure the science is actionable in meeting the specific needs surrounding a question or decision
EXAMPLE	Inform a state agency about the status and trends of herpetofauna diversity associated with a local wetland as an indicator of ecosystem health	Scientific data provided to US Fish and Wildlife Service regarding an interim rule on Bsal	Rapid detection of disease-induced declines in herpetofauna populations via continuous monitoring by the community such as the Herp Disease Alert System	Engagement of university students in non-lethal amphibian disease surveillance via the Student Network for Amphibian Pathogen Surveillance, or SNAPS	Engagement of tribal and first nations peoples in all stages of the research process

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.

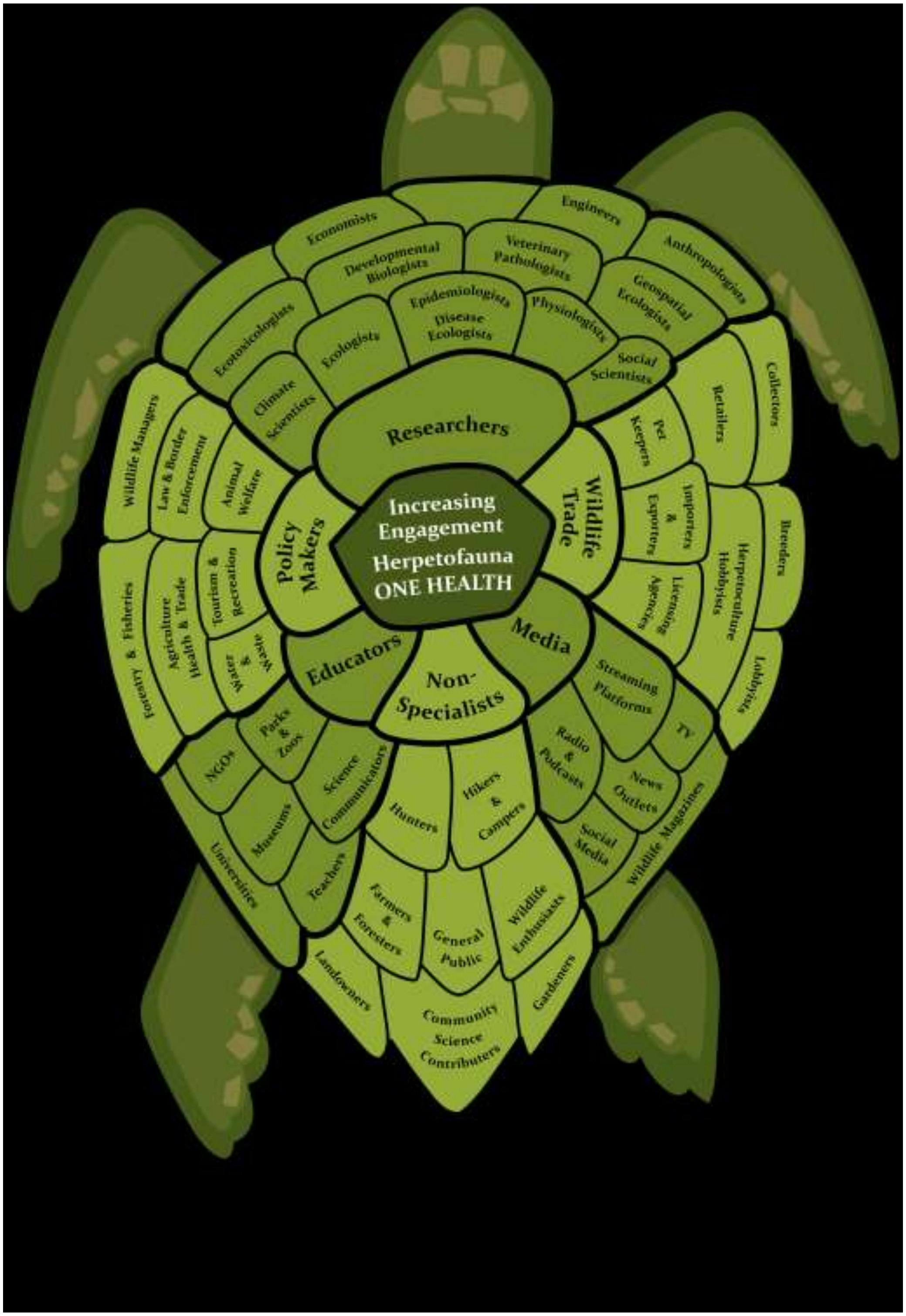

Figure 2. Visual Schematic representing the diverse stakeholders that can contribute to a successful One Health approach for herpetofauna. Credit: Natalie Claunch.

Table 1. Examples of Connections Between Herptile Species and Human Health

Herptile Class	**Connectionsto 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. ● 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. ● Antimicrobial peptides (AMP) from anuran skin can inhibit infection of human immune-deficiency virus (HIV). ● Skin secretions from *Phyllomedusa* frogs may be useful in treating drug-resistant infections.	(Elkan 1938) (Salehi *et al.* 2018) (VanCompernolle *et al.* 2005) (Azevedo Calderon *et al.* 2011)
	Indirect connectionsbenefits ● Amphibian collapse in Costa Rica and Panama is associated with increased incidence of the mosquito-borne human malaria. ● Insights from amphibian regenerative capabilities are informing advances in regenerative medicine.	(Springborn *et al.* 2022) (Mahapatra *et al.* 2023)
Reptiles	*Direct connectionsbenefits* ● The venom of *Bothrops* snakes has important antimicrobial and pharmacological properties. ● Venoms of *Heloderma* and various snake species are used in pharmaceutical drugs to treat things such as hypertension and Type 2 diabetes mellitus.	(Ciscotto *et al.* 2009) (Bordon *et al.* 2020)
	Indirect connectionsbenefits ● 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)

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”	(Walls *et al.* 2013)

		• Potential for habitat alteration, range shrinkage	
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)