# The Amplifying Effect of Environmental Stress on Ranavirus Outbreaks in Amphibians

Richard Barelds - s3897583

04-10-2024

Lequime Lab

Supervised by Dr. S.J.J. Lequime

## Abstract

Amphibians are facing unprecedented global declines, with over 40% of species threatened with extinction due to a combination of habitat destruction, pollution, climate change, and emerging infectious diseases. This essay explores the vulnerability of amphibians to environmental stressors and how these factors amplify their susceptibility to pathogens like ranavirus. Amphibians' permeable skin, reliance on aquatic and terrestrial habitats, and ectothermic nature make them highly sensitive to pollutants and temperature extremes, compromising their immune function. Additionally, habitat degradation increases their exposure to diseases by fragmenting populations and creating environments that foster pathogen spread. The essay emphasizes amphibians' critical ecological roles, including their contribution to nutrient cycling, pest control, and maintaining ecosystem health. Amphibian declines thus have cascading effects on biodiversity and ecosystem services. Conservation efforts must adopt integrated strategies addressing environmental degradation and disease management to mitigate these compounded threats and preserve amphibian populations globally.

## Table of contents



## Introduction

Amphibians, characterized by their complex life cycles and permeable skin, are particularly susceptible to environmental changes. Their vulnerability has led to a global crisis, with over 40% of species currently threatened with extinction due to habitat destruction, pollution, climate change, and the emergence of infectious diseases (Stuart et al., 2004; IUCN, 2022). These stressors have led to severe population declines and, in some cases, local extinctions, making amphibians one of the most vulnerable vertebrate groups globally (Wake & Vredenburg, 2008). This amphibian extinction crisis represents one of the most significant biodiversity losses in recent history.

Amphibians are early biological warning signs due to their sensitivity to environmental changes, particularly contaminants and climate shifts (Boone et al., 2024; Bucciarelli et al., 2020). Their permeable skin, crucial for respiration and water absorption, makes them highly vulnerable to environmental contaminants and pathogens (Wells, 2019). Amphibians depend on aquatic and terrestrial habitats throughout their life cycle, increasing their exposure to various environmental stressors. This extensive exposure has contributed significantly to the decline of amphibian species across the globe.

The loss of amphibians has severe ecological consequences. Amphibians play critical roles as predators and prey in aquatic and terrestrial food webs, helping maintain the balance of ecosystems by regulating insect populations and serving as a food source for numerous other species. Their decline could lead to unchecked insect populations, potentially resulting in increased agricultural damage and the spread of certain zoonotic diseases. For instance, a reduction in amphibian populations due to the spread of *Batrachochytrium dendrobatidis* has been linked to increased malaria prevalence, transmitted by mosquitoes (Springborn et al., 2022). Similarly, research has shown that tadpoles from various amphibian species prey on the eggs of *Aedes aegypti*, the primary vector for dengue. This highlights the crucial role amphibians play in controlling major disease-carrying mosquitoes, and the decline of amphibians could lead to increased rates of diseases like dengue (Bowatte et al., 2013).

Amphibians also act as keystone species in many ecosystems, particularly wetlands, contributing to essential nutrient cycling. As larvae, amphibians feed on algae and detritus in ponds and streams, helping regulate primary productivity and improve water quality. As adults, they transport essential nutrients like nitrogen and phosphorus between aquatic and terrestrial habitats, supporting plant growth and maintaining ecosystem health (Ranvestel et al., 2004; Whiles et al., 2013). Without amphibians, these nutrient flows could be disrupted, potentially leading to poor water quality, algal blooms, and reduced plant productivity. In addition to their roles in nutrient cycling and food webs, amphibians indirectly support agriculture and public health by controlling pest populations and helping purify water (West, 2018). However, despite their importance, amphibians face numerous threats from environmental changes, putting their populations at serious risk.

Amphibians' susceptibility to environmental stressors is closely tied to their physiology and life history. Their permeable skin allows them to absorb contaminants such as pesticides and heavy metals from their environment, compromising their health. Amphibians are often found in or around shallow water bodies, further exposing them to pollutants like agricultural runoff and industrial waste, which interfere with their reproductive success and development (Hayes et al., 2010). Their reliance on these delicate environments makes them particularly vulnerable to habitat changes.

In addition to their exposure to pollutants, amphibians' ectothermic nature further amplifies their vulnerability. As ectotherms, amphibians rely on external temperatures to regulate their body functions. This dependence makes them particularly sensitive to the effects of climate change, as rising global temperatures and increased weather variability disrupt their life cycles and habitats (Raffel et al., 2013). For example, some amphibians breed in temporary ponds dependent on seasonal rainfall. With shifting precipitation patterns due to climate change, these ponds are drying up before tadpoles can fully develop, leading to reproductive failures and population declines (Donnelly & Crump, 1998). This mismatch between life cycles and environmental cues is becoming increasingly common as climate change progresses.

In addition to the impact of climate change, habitat destruction has also played a key role in amphibian declines. Wetland drainage, deforestation, and urban development fragment landscapes and reduce the availability of critical breeding and foraging sites (Cushman, 2006). As habitats shrink, amphibians are forced into smaller, more isolated populations, which reduces genetic diversity and weakens their ability to adapt to environmental changes (Hitchings & Beebee, 1998). Habitat fragmentation also disrupts migration patterns, preventing amphibians from reaching suitable environments at different life cycle stages, further compounding their vulnerability.

In addition to habitat loss and climate change, pollution is a widespread and compounding threat to amphibian populations. Many pollutants, including herbicides and pesticides like atrazine, have been shown to interfere with amphibian development and reproduction (Solomon et al., 2008). These pollutants often accumulate in the aquatic environments that amphibians depend on for breeding, directly affecting survival rates and the overall health of populations. Chronic exposure to these pollutants, habitat degradation, and climate shifts place amphibians under continuous environmental stress, making it difficult for populations to recover from declines.

One of the most devastating consequences of amphibians' broad vulnerability to environmental stressors is the emergence and spread of infectious diseases. Among these, ranavirus has had particularly severe impacts, causing widespread population crashes and localized extinctions in amphibians across the globe (Gray & Chinchar, 2015). *Ranavirus* is a genus of viruses in the family *Iridoviridae* that primarily affects ectothermic vertebrates, including amphibians, reptiles, and fish. These highly virulent pathogens attack amphibian tissues, leading to hemorrhages, organ failure, and death, especially in populations already weakened by environmental degradation. Amphibians in polluted or fragmented habitats are particularly susceptible to ranavirus, as environmental stress increases their vulnerability to infection.

Environmental changes and ranavirus outbreaks are tightly linked. The increasing number of stressors amphibians face weakens their ability to fend off pathogens, leading to more severe disease outbreaks and population collapses. Ranavirus is a clear example of how emerging pathogens further accelerate amphibian populations' decline under environmental stress.

This essay explores how environmental stressors, such as temperature extremes, pollution, and habitat degradation, contribute to amphibians' increased vulnerability to pathogens like ranavirus. By examining these interactions, the essay emphasizes the urgent need for conservation strategies that address environmental degradation and disease management. Safeguarding amphibians from extinction is critical for biodiversity and maintaining the ecosystems and services they support.

**Amphibians and Environmental Stressors: Impacts on Disease Susceptibility**

To fully grasp how diseases caused by ranaviruses exploit amphibian vulnerabilities, it is essential to examine how specific environmental stressors individually and collectively disrupt amphibian health and immunity. Each factor, such as temperature extremes, pollution, and habitat degradation, weakens amphibians' immune defenses while creating conditions that favor increased pathogen transmission and virulence. Furthermore, studies suggest these stressors may interact, resulting in more rapid pathogen evolution and greater disease severity (Carrasco et al., 2021).

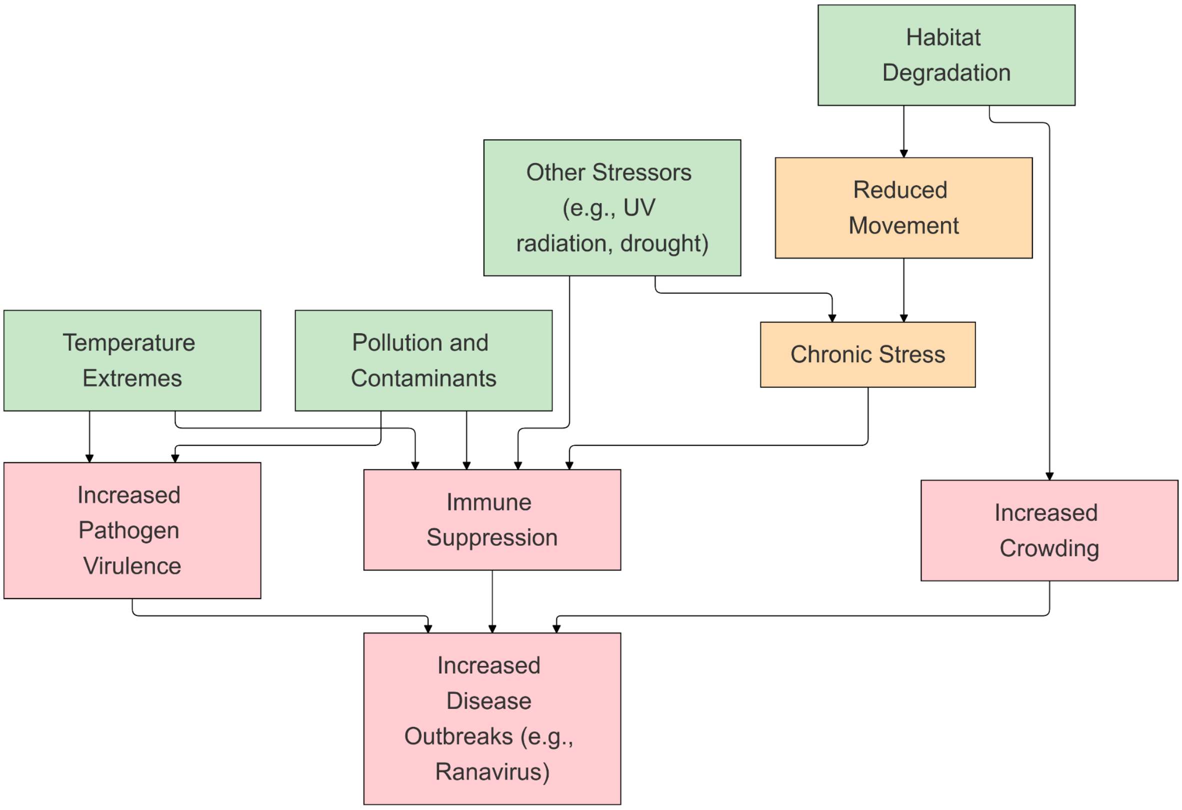


*Figure 1: Flowchart illustrating the progression of environmental stressors (green) to intermediate effects (orange) and final consequences (red) leading to increased disease outbreaks caused by pathogens such as ranavirus in amphibians.*

### *Temperature Extremes*

Temperature fluctuations, especially warming trends, profoundly disrupt amphibian immune function and enhance pathogen virulence. Elevated temperatures suppress amphibian immune responses and accelerate pathogen replication rates, leading to more severe infections. Thermal stress reduces the production and efficiency of immune cells like lymphocytes, which play a critical role in defending against infections. Studies have shown that amphibians produce fewer antimicrobial peptides under heat stress, making them more susceptible to infection (Rollins-Smith, 2017). Additionally, heat stress impairs the immune response by limiting the production of antibodies in amphibians, further weakening their defenses against infections (Rollins-Smith & Le Sage, 2023).

For example, North et al. (2015) found that warmer summers in the United Kingdom were associated with increased ranavirus outbreaks in *Rana temporaria*, suggesting that elevated temperatures enhance pathogen spread by weakening host defenses and promoting pathogen replication. Similarly, Raffel et al. (2013) demonstrated that even short-term temperature variability can amplify disease impacts by triggering a thermal mismatch between amphibians and pathogens. Pathogens often thrive under warmer conditions, while amphibian immune systems struggle to cope, leading to greater pathogen loads and increased disease severity (Cohen et al., 2017). Research from South Korea supports these findings, showing that amphibians in warmer regions had higher rates of ranavirus infection due to compromised immune responses in elevated temperatures (Roh et al., 2022). The ability of pathogens to multiply faster in warmer conditions, combined with suppressed amphibian immunity, highlights climate change's critical role in altering disease dynamics within amphibian populations.

*Pollution and Contaminants*

Pollutants, including pesticides, heavy metals, and agricultural runoffs, pose significant threats to amphibian health by impairing their immune systems and amplifying pathogen virulence. Chemical pollutants such as atrazine, a widely used herbicide in agriculture, disrupt amphibian hormonal regulation and immune function, leaving them vulnerable to pathogens (Hayes et al., 2010). Prolonged exposure to contaminants can reduce the production of critical immune cells like leukocytes, leaving amphibians defenseless against pathogens like ranaviruses (Valbona et al., 2012; Silva et al., 2020). Pesticides, particularly organophosphates and neonicotinoids, have been shown to interfere with normal immune function, significantly lowering amphibian resilience to ranavirus outbreaks (Rios et al., 2017).

Moreover, pollutants can also directly alter the virulence of pathogens. Certain environmental toxins may increase the mutation rates of pathogens, leading to more aggressive strains (Searle et al., 2011). Hoverman et al. (2012) documented widespread ranavirus infections in amphibian populations in Tennessee, United States, where poor water quality and chemical pollutants were significant contributing factors. In the agricultural landscapes of California, research found that ponds contaminated with pesticides and fertilizers had higher rates of ranavirus infections in local amphibian populations, with water quality directly affecting the pathogen's persistence and virulence (Tornabene et al., 2018). This combination of immune suppression and heightened pathogen virulence in polluted environments highlights the synergistic effects of pollution on amphibian disease dynamics, amplifying the overall impact on amphibian populations.

*Habitat Degradation*

Habitat fragmentation, wetland loss, and deteriorating water quality contribute to the decline of amphibian populations by creating chronic stress conditions that impair immune function and increase exposure to pathogens. In addition, fragmented habitats restrict amphibian movement, reducing access to vital resources and suitable breeding sites. However, they also cause chronic stress, weakening amphibians' immune defenses over time (Cushman, 2006). Stressed amphibians exhibit lower levels of immune surveillance, making them more prone to infections (Blaustein et al., 2012).

At the same time, habitat degradation often increases pathogen contact rates. When wetlands shrink or fragment, amphibians are forced into smaller areas, increasing the density of individuals in these compromised environments. This crowding facilitates the spread of infectious pathogens like ranavirus, which thrive in environments where animals are in close contact (Gray et al., 2009). Price et al. (2014) observed that northern Spain's habitat fragmentation and temperature extremes led to significant ranavirus-related mortality in *Lithobates sylvaticus* populations. Similarly, Brunner et al. (2015) found that severe ranavirus outbreaks in *Ambystoma tigrinum* populations were linked to drought conditions in the southwestern U.S., where habitat degradation and water scarcity had amplified pathogen transmission. In addition, research in the United Kingdom showed that habitat fragmentation, particularly in urban areas, significantly worsened the effects of ranavirus outbreaks by increasing population density and reducing amphibian mobility (Campbell et al., 2020).

The combined effects of habitat degradation, such as reduced immune function, increased crowding, and environmental stress, create ideal conditions for increasing pathogen virulence. Weakened amphibians not only have less ability to fight off infections, but the pathogens themselves may become more virulent as they evolve and adapt to stressed host populations and degraded environments (Brunner et al., 2015).

*Other Stressors*

Additional stressors, such as UV radiation, drought, and fluctuating water quality, further amplify amphibians' vulnerability to diseases. UV radiation damages amphibian skin, a critical barrier against pathogens, and has been linked to increased ranavirus outbreaks by amplifying immune suppression caused by environmental pollutants. When this barrier is compromised, amphibians become more susceptible to infections (Blaustein et al., 2010), while pathogens in UV-exposed environments may develop adaptations that make them more resilient and virulent (Bancroft et al., 2008).

Drought conditions reduce the availability of aquatic habitats, forcing amphibians into higher densities in shrinking water bodies, which increases the likelihood of disease transmission. Pathogens like ranavirus thrive in stressed environments, where crowding and poor water quality allow the disease to spread more quickly. Brunner et al. (2015) highlighted that drought-stricken habitats saw higher transmission rates of ranavirus in *A. tigrinum*, demonstrating the compounded effects of environmental stressors on amphibian health.

Furthermore, the impact of extreme weather events, including droughts and floods, is expected to increase in the coming decades, further amplifying the vulnerability of amphibians to ranavirus outbreaks (Campbell et al., 2020). Flooding, in particular, disrupts breeding sites, displaces amphibian populations, and often brings pollutants, such as agricultural runoff and sewage, into aquatic habitats. This introduces toxins into amphibian environments, degrading water quality and amplifying immune suppression while simultaneously creating favorable conditions for ranavirus to persist and spread. Amphibians in post-flood environments are left facing a combination of habitat destruction, toxic exposure, and heightened disease transmission risks. Research suggests that post-flood environments, with their high pathogen load and weakened host defenses, are ideal for large-scale ranavirus outbreaks (Tornabene et al., 2018).

Moreover, light pollution is an emerging but often overlooked stressor, particularly in urbanized areas. Excessive artificial light disrupts nocturnal behaviors such as feeding and mating, vital for amphibians' survival. Altered light conditions can affect amphibians' circadian rhythms, leading to hormonal imbalances and weakening immune defenses. Increased exposure to light pollution may increase susceptibility to diseases like ranavirus by increasing physiological stress and impairing immune responses (Touzot et al., 2021). In such environments, pathogens can exploit the weakened amphibians, increasing their virulence, while poor water quality, light pollution, and other stressors further compromise amphibians' already-suppressed immune defenses. The combined impact of these stressors leaves amphibians highly vulnerable to widespread disease outbreaks, pushing many populations to the brink of collapse.

**Implications for Conservation**

The combined impacts of environmental stressors and disease pose significant challenges for amphibian conservation, mainly because these factors interact in complex ways. Traditional conservation efforts, which may focus on addressing habitat loss or managing specific diseases, often fall short in tackling the multifaceted nature of amphibians' threats. The persistence of environmental stressors, such as habitat degradation, pollution, and climate change, continues to create conditions that amplify disease risks, complicating efforts to protect vulnerable populations (Grant et al., 2017). For instance, controlling ranavirus outbreaks becomes increasingly challenging when amphibians remain exposed to polluted water, extreme temperatures, or fragmented habitats that continuously stress their immune systems (Gray et al., 2009).

Effective conservation strategies must adopt an integrated approach that targets habitat quality and disease management. Enhancing habitat connectivity through the creation of wildlife corridors can alleviate the impacts of fragmentation, allowing amphibians to move between habitats, access necessary resources, and reduce disease transmission by avoiding overcrowded areas (Cushman, 2006). Wetland restoration and improving water quality are crucial for creating healthier environments that bolster amphibian resilience against pathogens (Hayes et al., 2010). Managing water resources to mimic natural hydrological patterns can help sustain aquatic habitats during critical breeding periods, reducing the impact of drought and water scarcity on amphibian populations (Brunner et al., 2015).

Adaptive management is essential in this context, as it continuously monitors environmental conditions and disease prevalence to guide responsive actions (Westgate et al., 2013). Disease surveillance programs can help identify areas where amphibians are particularly vulnerable, enabling targeted interventions like habitat enhancements, controlled breeding programs, or temporary site closures to reduce pathogen spread (Gray et al., 2009). Additionally, reducing exposure to pollutants through sustainable agricultural practices can improve the overall health of amphibian habitats, lessening the compounding stress that increases disease susceptibility (Mann et al., 2009; Camacho-Rozo & Camacho-Reyes, 2022).

Conservation strategies must also be dynamic and forward-thinking, recognizing that climate change will continue to reshape the challenges amphibians face. Integrating habitat restoration, pollution control, and proactive disease management can mitigate the compounded threats of environmental stress and disease, helping to safeguard amphibian populations amid rapidly changing conditions (Park & Do, 2023).

**Broader Implications**

While this essay focuses on the specific case of ranavirus in amphibians, the dynamics between environmental stressors and disease transmission reveal broader ecological patterns with far-reaching implications. Amphibians, as bioindicators, highlight how stressors such as temperature extremes, pollution, and habitat degradation amplify disease transmission. This is not an isolated phenomenon; similar stress-disease dynamics have been observed in other taxa, including fish, reptiles, and mammals (Carlson et al., 2022). The health of amphibian populations often mirrors the overall health of ecosystems, and their decline due to environmental stressors or disease has far-reaching effects on biodiversity and ecosystem function (Hayden & Blom, 2024). As both predators and prey, amphibians play critical roles in maintaining ecological balance, and their vulnerability to disease can disrupt food webs, nutrient cycling, and ecosystem stability.

The concept of "pathogen pollution" illustrates how human activities, such as global trade and land-use changes, introduce pathogens into new ecosystems where they can thrive. For instance, the global amphibian pet trade has been linked to the spread of ranavirus and other pathogens into previously unaffected regions (Herath et al., 2021). This cross-boundary movement of pathogens, facilitated by human commerce, increases the risk of disease transmission across species. In ecosystems where amphibians are central to food webs, their decline due to pathogens like ranavirus can destabilize predator-prey relationships and compromise the health of both aquatic and terrestrial ecosystems (Gray et al., 2009).

These pathogen-driven disruptions are not limited to ranavirus. For example, the spread of fungal pathogens like *Batrachochytrium dendrobatidis* and *Batrachochytrium* *salamandrivorans* shares similarities with ranavirus regarding their ecological impacts. Both pathogens disproportionately affect amphibians, thrive under environmental stress, and are amplified by factors such as habitat degradation, pollution, and temperature fluctuations. In both cases, pathogens can persist in the environment, creating reservoirs that make it difficult for affected populations to recover and increasing the risk of future outbreaks (Woodhams et al., 2018). This emphasizes the importance of integrating disease management into broader conservation strategies, particularly in regions undergoing rapid environmental change.

One critical area where these broader dynamics become particularly relevant is the emergence of zoonotic and vector-borne diseases. Human-driven environmental changes—such as deforestation, agricultural expansion, and habitat degradation—are increasingly linked to the spread of zoonotic diseases. Morand and Lajaunie (2021) demonstrated that deforestation in tropical regions is correlated with a rise in zoonotic disease outbreaks, while land-use changes such as reforestation in non-tropical areas can also create conditions favorable to disease spread. These findings show that habitat alteration not only affects biodiversity but also directly influences pathogen transmission, leading to cascading ecological effects.

The observed effects of environmental stressors on wildlife disease outbreaks underscore the need to address the root causes of disease dynamics. These dynamics have global relevance, particularly in the context of zoonotic diseases like avian influenza and coronaviruses, where habitat destruction and climate change are amplifying transmission risks (Daszak et al., 2001; Jones et al., 2008). Just as environmental changes have increased disease vulnerability in amphibians, similar processes are driving the emergence of zoonotic diseases that impact human populations. This underscores the interconnectedness of wildlife and human health, highlighting the urgent need for ecosystem-based approaches to conservation, disease management, and public health to prevent future pandemics and biodiversity loss on a global scale.

**Future Directions**

In light of these broader implications, future research should aim to extend the findings from amphibian studies to other vulnerable species, exploring how stress-disease dynamics manifest across ecosystems. Amphibians provide a critical model, but many other taxa, such as reptiles, fish, birds, and mammals, also experience similar stress-induced vulnerabilities that amplify disease spread in response to environmental changes. Understanding whether these dynamics are present in other species is essential for predicting how ecosystems will respond to ongoing climate and habitat disruptions. The connections between habitat loss, climate change, and disease transmission observed in amphibians can serve as a model for understanding emerging diseases in other species, particularly in zoonotic disease outbreaks.

Future research should also focus on cross-species transmission risks, as diseases originating in one taxon often affect multiple species, including humans, further complicating conservation efforts and human health strategies. For instance, exploring how pathogens like ranavirus or *B. dendrobatidis* spill over into different hosts under environmental stress could reveal critical insights into how diseases spread between wildlife populations and human communities. By focusing on the systemic causes of biodiversity loss, conservationists and policymakers can develop more comprehensive strategies that address species-specific threats and underlying environmental drivers, such as habitat restoration, pollution control, and climate adaptation measures.

Additionally, research into how ecosystems regulate disease transmission—through factors like biodiversity, population density, and predator-prey relationships—can inform practices that enhance ecosystem resilience and reduce disease risks. In doing so, we can mitigate the broader risks environmental stressors pose to global biodiversity. Ultimately, a more integrated, ecosystem-based approach to conservation and disease management will be critical in addressing biodiversity loss and the escalating risks of zoonotic disease outbreaks.

**Conclusion**

Amphibians' vulnerability to environmental stressors such as temperature extremes, pollution, and habitat degradation offers a specific case study of ranavirus and a window into understanding the broader consequences of environmental change on disease dynamics. This case illustrates how environmental stress weakens species' immune defenses, creating favorable conditions for pathogens to thrive. In this way, amphibians serve as indicators of ecosystem health, signaling broader ecological disruptions that can have cascading effects on biodiversity and ecosystem stability.

The lessons from this case highlight the urgency of integrated conservation efforts that address the direct and indirect drivers of species decline. Addressing environmental stressors is critical for amphibian conservation and protecting the health of entire ecosystems. Climate change mitigation, pollution control, habitat restoration, and stronger regulations on land use are essential to curb the rise of disease outbreaks in wildlife and, potentially, humans.

The findings presented in this essay suggest that the combined impacts of stressors and disease are not limited to amphibians but may also foreshadow similar risks to other taxa, thereby emphasizing the need for ecosystem-based conservation approaches. Furthermore, as climate change accelerates and human activities continue to disrupt natural habitats, interdisciplinary collaboration between ecologists, public health experts, and policymakers will be vital in developing strategies that protect biodiversity and human health.

Ultimately, the amphibian-ranavirus case underscores the need for proactive conservation measures beyond species-specific interventions to address the underlying environmental changes driving disease emergence. By adopting an ecosystem-wide approach, we can mitigate the interconnected risks of species loss, ecosystem degradation, and the rise of zoonotic diseases, contributing to global biodiversity preservation and public health resilience.

## Literature


Bancroft, B. A., Baker, N. J., & Blaustein, A. R. (2008). A meta-analysis of the effects of ultraviolet B radiation and its synergistic interactions with pH, contaminants, and disease on amphibian survival. Conservation Biology, 22(4), 987-996.

Blaustein, A. R., Walls, S. C., Bancroft, B. A., Lawler, J. J., Searle, C. L., & Gervasi, S. S. (2010). Direct and indirect effects of climate change on amphibian populations. Diversity, 2(2), 281-313.

Blaustein, A. R., Gervasi, S. S., Johnson, P. T., Hoverman, J. T., Belden, L. K., Bradley, P. W., & Xie, G. Y. (2012). Ecophysiology meets conservation: understanding the role of disease in amphibian population declines. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1596), 1688-1707.

Bowatte, G., Perera, P., Senevirathne, G., Meegaskumbura, S., & Meegaskumbura, M. (2013). Tadpoles as dengue mosquito (Aedes aegypti) egg predators. Biological Control, 67(3), 469-474.

Boone, M. D., Hua, J., Gabor, C. R., Gomez-Mestre, I., Katzenberger, M., McMahon, T. A., & Rumschlag, S. L. Ecotoxicology: amphibian vulnerability to chemical contamination. Amphibian conservation action plan, 89.

Brunner, J. L., Storfer, A., Gray, M. J., & Hoverman, J. T. (2015). Ranavirus ecology and evolution: from epidemiology to extinction. Ranaviruses: Lethal pathogens of ectothermic vertebrates, 71-104

Bucciarelli, G. M., Clark, M. A., Delaney, K. S., Riley, S. P., Shaffer, H. B., Fisher, R. N., ... & Kats, L. B. (2020). Amphibian responses in the aftermath of extreme climate events. Scientific Reports, 10(1), 3409.

Camacho-Rozo, C. P., & Camacho-Reyes, J. A. (2022). Effect of agricultural pesticides and land use intensification on amphibian larval development. In Animal Welfare-New Insights. IntechOpen.

Campbell, L. J., Pawlik, A. H., & Harrison, X. A. (2020). Amphibian ranaviruses in Europe: important directions for future research. Facets, 5(1), 598-614..

Carlson, C. J., Albery, G. F., Merow, C., Trisos, C. H., Zipfel, C. M., Eskew, E. A., ... & Bansal, S. (2022). Climate change increases cross-species viral transmission risk. Nature, 607(7919), 555-562.

Carrasco, G. H., de Souza, M. B., & de Souza Santos, L. R. (2021). Effect of multiple stressors and population decline of frogs. Environmental Science and Pollution Research, 1-9.

Cohen, J. M., Venesky, M. D., Sauer, E. L., Civitello, D. J., McMahon, T. A., Roznik, E. A., & Rohr, J. R. (2017). The thermal mismatch hypothesis explains host susceptibility to an emerging infectious disease. Ecology letters, 20(2), 184-193.

Cushman, S. A. (2006). Effects of habitat loss and fragmentation on amphibians: a review and prospectus. Biological conservation, 128(2), 231-240.

Daszak, P., Cunningham, A. A., & Hyatt, A. D. (2001). Anthropogenic environmental change and the emergence of infectious diseases in wildlife. Acta tropica, 78(2), 103-116.

Donnelly, M. A., & Crump, M. L. (1998). Potential effects of climate change on two neotropical amphibian assemblages. Climatic change, 39(2), 541-561.

Grant, E. H. C., Muths, E., Katz, R. A., Canessa, S., Adams, M. J., Ballard, J. R., ... & White, C. L. (2017). Using decision analysis to support proactive management of emerging infectious wildlife diseases. Frontiers in Ecology and the Environment, 15(4), 214-221.

Gray, M. J., Miller, D. L., & Hoverman, J. T. (2009). Ecology and pathology of amphibian ranaviruses. Diseases of aquatic organisms, 87(3), 243-266.

Gray, M. J., & Chinchar, V. G. (2015). Ranaviruses: lethal pathogens of ectothermic vertebrates. Springer Nature.

Hayden Bofill, S. I., & Blom, M. P. (2024). Climate change from an ectotherm perspective: evolutionary consequences and demographic change in amphibian and reptilian populations. Biodiversity and Conservation, 33(3), 905-927.

Hayes, T. B., Falso, P., Gallipeau, S., & Stice, M. (2010). The cause of global amphibian declines: a developmental endocrinologist's perspective. Journal of Experimental Biology, 213(6), 921-933.

Herath, J., Ellepola, G., & Meegaskumbura, M. (2021). Patterns of infection, origins, and transmission of ranaviruses among the ectothermic vertebrates of Asia. Ecology and Evolution, 11(22), 15498-15519.

Hoverman, J. T., Gray, M. J., Miller, D. L., & Haislip, N. A. (2012). Widespread occurrence of ranavirus in pond-breeding amphibian populations. EcoHealth, 9, 36-48.

IUCN. (2022). The IUCN Red List of Threatened Species. Amphibian Statistics. [https://www.iucnredlist.org](https://www.iucnredlist.org)

Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L., & Daszak, P. (2008). Global trends in emerging infectious diseases. Nature, 451(7181), 990-993.

Mann, R. M., Hyne, R. V., Choung, C. B., & Wilson, S. P. (2009). Amphibians and agricultural chemicals: review of the risks in a complex environment. Environmental pollution, 157(11), 2903-2927.

Morand, S., & Lajaunie, C. (2021). Outbreaks of vector-borne and zoonotic diseases are associated with changes in forest cover and oil palm expansion at global scale. Frontiers in veterinary science, 8, 661063.

North, A. C., Hodgson, D. J., Price, S. J., & Griffiths, A. G. (2015). Anthropogenic and ecological drivers of amphibian disease (ranavirosis). *PloS One, 10*(6), e0127037.

Park, J. K., & Do, Y. (2023). Current state of conservation physiology for amphibians: Major research topics and physiological parameters. Animals, 13(20), 3162.

Price, S. J., Garner, T. W., Nichols, R. A., Balloux, F., Ayres, C., de Alba, A. M. C., & Bosch, J. (2014). Collapse of amphibian communities due to an introduced Ranavirus. Current Biology, 24(21), 2586-2591.

Raffel, T. R., Romansic, J. M., Halstead, N. T., McMahon, T. A., Venesky, M. D., & Rohr, J. R. (2013). Disease and thermal acclimation in a more variable and unpredictable climate. Nature Climate Change, 3(2), 146-151.

Ranvestel, A. W., Lips, K. R., Pringle, C. M., Whiles, M. R., & Bixby, R. J. (2004). Neotropical tadpoles influence stream benthos: evidence for the ecological consequences of decline in amphibian populations. Freshwater Biology, 49(3), 274-285.

Rios, F. M., Wilcoxen, T. E., & Zimmerman, L. M. (2017). Effects of imidacloprid on Rana catesbeiana immune and nervous system. Chemosphere, 188, 465-469.

Roh, N., Park, J., Kim, J., Kwon, H., & Park, D. (2022). Prevalence of Ranavirus infection in three anuran species across South Korea. Viruses, 14(5), 1073.

Rollins-Smith, L. A. (2017). Amphibian immunity–stress, disease, and climate change. Developmental & Comparative Immunology, 66, 111-119.

Rollins-Smith, L. A., & Le Sage, E. H. (2023). Heat stress and amphibian immunity in a time of climate change. Philosophical Transactions of the Royal Society B, 378(1882), 20220132.

Searle, C. L., Gervasi, S. S., Hua, J., Hammond, J. I., Relyea, R. A., Olson, D. H., & Blaustein, A. R. (2011). Differential host susceptibility to Batrachochytrium dendrobatidis, an emerging amphibian pathogen. Conservation Biology, 25(5), 965-974.

Silva, M. B. D., Fraga, R. E., Nishiyama, P. B., Silva, I. S. S. D., Costa, N. L. B., de Oliveira, L. A. A., ... & Juncá, F. A. (2020). Leukocyte profiles in Odontophrynus carvalhoi (Amphibia: Odontophrynidae) tadpoles exposed to organophosphate chlorpyrifos pesticides. Water, Air, & Soil Pollution, 231(7), 372.

Solomon, K. R., Carr, J. A., Du Preez, L. H., Giesy, J. P., Kendall, R. J., Smith, E. E., & Van Der Kraak, G. J. (2008). Effects of atrazine on fish, amphibians, and aquatic reptiles: a critical review. Critical reviews in toxicology, 38(9), 721-772.

Springborn, M. R., Weill, J. A., Lips, K. R., Ibáñez, R., & Ghosh, A. (2022). Amphibian collapses increased malaria incidence in Central America. Environmental Research Letters, 17(10), 104012.

Stuart, S. N., Chanson, J. S., Cox, N. A., Young, B. E., Rodrigues, A. S., Fischman, D. L., & Waller, R. W. (2004). Status and trends of amphibian declines and extinctions worldwide. Science, 306(5702), 1783-1786.

Tornabene, B. J., Blaustein, A. R., Briggs, C. J., Calhoun, D. M., Johnson, P. T., McDevitt‐Galles, T., ... & Hoverman, J. T. (2018). The influence of landscape and environmental factors on ranavirus epidemiology in a California amphibian assemblage. Freshwater biology, 63(7), 639-651.

Touzot, M., Lefebure, T., Lengagne, T., Secondi, J., Dumet, A., Konecny-Dupre, L., ... & Mondy, N. (2021). Large-scale deregulation of gene expression by artificial light at night in tadpoles of common toads. bioRxiv, 2021-07.

Valbona, A., Adiola, B., Eldores, S., & Alketa, G. (2012). Effects of pollution on amphibian blood parameters (Ranidae: Rana balcanica & Rana lessonae) from the Albania's coastal zone. In Conference: International conference MarCoastEcos (Vol. 1, pp. 207-213).

Wake, D. B., & Vredenburg, V. T. (2008). Are we in the midst of the sixth mass extinction? A view from the world of amphibians. Proceedings of the National Academy of Sciences, 105(supplement_1), 11466-11473.

West, J. (2018). Importance of amphibians: A synthesis of their environmental functions, benefits to humans, and need for conservation.

Westgate, M. J., Likens, G. E., & Lindenmayer, D. B. (2013). Adaptive management of biological systems: a review. Biological Conservation, 158, 128-139.

Wells, K. D. (2019). The ecology and behavior of amphibians. University of Chicago press.

Whiles, M. R., Hall, R. O., Dodds, W. K., Verburg, P., Huryn, A. D., Pringle, C. M., ... & Connelly, S. (2013). Disease-driven amphibian declines alter ecosystem processes in a tropical stream. Ecosystems, 16, 146-157.

Woodhams, D. C., Barnhart, K. L., Bletz, M. C., Campos, A. J., Ganem, S. J., Hertz, A., ... & Tokash-Peters, A. G. (2018). Batrachochytrium: biology and management of amphibian chytridiomycosis. eLS, 1-18.