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(Review Article)

Impact of climate change on the reproduction, distribution and abundance of herpetofauna: A review of Literature

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Abstract

The purpose of this paper is to review and assess published literature on the impact of climate change on herpetofauna. A systematic approach was used to accumulate research works of literature on "Impact of climate change on herpetofauna." A total of forty (40) research papers published between the years 1930 to 2023 were accessed and used for this review. Tables were used to present all results. A subjective approach was used to select the topics: impact of climate change and herpetofauna. In this paper, nine (9) detrimental impacts of climate change were assessed and presented; four (4) which are specific to reptiles and five (5) which are specific to amphibians. The published papers established that extreme weather conditions, such as high temperature, heavy precipitation, synergistic vulnerabilities, ultraviolet radiation and repercussions of ectotherm metabolic rate all contribute to the global climate change that are affecting the reproduction, distribution and abundance of herpetofauna. This review highlights the fact that more extensive studies on the impact of climate change on herpetofauna should be done in neotropical countries since there is a paucity of such information on research and published data in these biodiversity rich regions.

Keywords: Climate change; Temperature; Precipitation; Herpetofauna; Reptiles; Amphibians

1. Introduction

Currently, scientists, governments, and policy planners face a number of global concerns related to climate change, its effects on biotic and abiotic ecosystem components, and the implementation of mitigation strategies. According to data from Walther *et al*. (2002) and the IPCC (2007), the earth's surface has warmed by 0.6 °C during the previous 100 years, and at the current rate of greenhouse gas emissions, the world's air temperature would likely rise by 1.5 to 4.5 °C by the end of the 21st century. Such variations in global temperature have a variety of effects, including glacial melt and sea level rise, unusual weather conditions like floods and droughts, intense but brief periods of rainfall, disease infestations, changes in agricultural practices, and various effects on flora and fauna [32] [65] [73] [80] [96] [101] [108] [153].

There are about 20,000 extant amphibians and reptiles, with new species being discovered annually [54] [62] [144]. Unfortunately, herpetofauna are among the most endangered vertebrate groups, with at least 41% of amphibians and 21% of reptiles deemed threatened [16] [56] [59] [61] [69] [71] [90] [101]. Estimates imply that amphibians will become extinct at a rate of almost 7% over the next century [6] [61] [90]. This is due to the majority of the usual causes of biodiversity loss in general: habitat loss and degradation, unsustainable use, infectious illnesses, etc. [39] [56] [61] [81] [90] [97] [134]. While the majority of the above have resulted in local or regional losses of herpetofaunal diversity, global climate change is a large-scale threat that interacts with all of the others and has far-reaching implications for herpetofaunal diversity [61] [84] [101] [139].

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Temperature and precipitation, for example, have a significant impact on the biology of amphibians and reptiles [61] [144]. Changes in the expected distribution of ectotherms, such as amphibians and reptiles, reflect temperature changes more closely than endotherms [9] [61]. Temperature biology confines herpetofauna to a narrow range of climatic circumstances, yet species can adapt behavioral tactics to preserve optimal or preferred temperature conditions [8] [61]. Many herpetofauna are projected to encounter limited activity windows and significant physiological costs when temperatures rise [35] [61]. This is an even bigger concern for tropical herpetofauna because thermal tolerance ranges are already low and many species currently function at the upper end of their ideal thermal ranges [60] [61] [68]. Many amphibians that synchronize their mating activities with certain meteorological conditions can be affected by changes in precipitation intensity and timing [21] [61]. Temperature and precipitation patterns can change the type, shape, and content of vegetation, as well as the availability of food and shelter, and the predator-prey/parasite-host dynamics for many species [14] [21] [61] [101] [102].

There is some indication that increasing temperature can diminish amphibian resistance to the fungal infection *Batrachochytrium dendrobatidis* (commonly known as the Bd fungus), which is now regarded as one of the primary causes of amphibian extinction [61] [110]. Herpetofaunal responses to such changes could take one of three forms: spatial changes (e.g., range reductions, shifts, and changes in species abundance), temporal changes (e.g., changes in daily or seasonal activity patterns and breeding phenology), and physiological or genetic changes (e.g., changes in preferred active body temperatures) [21] [60] [61] [101].

In different groups of organisms, including mammals, birds, herpetofauna, butterflies, and plants, the impact of a changing climate is seen as changes in phenology, upward shifts along latitude and altitude, extinction of species, and changes in community and trophic dynamics [65] [73] [108] [121] [147]. Most bird species now face a high risk of extinction as a result of climatic change events [32] [121] [152]. According to Sekercioğlu *et al*. (2012), a 3.5 °C surface temperature increase will cause the extinction of 600–900 land birds by 2100, with additional extinctions occurring at a rate of 100–500 per degree increase. Birds all across the world are frequently shown to lose their ability to reproduce and experience population declines [32] [122]. Lower animals, such as reptiles and amphibians, are ectothermic and as a result are impacted by climate change either directly or indirectly [10] [32]. The biggest threats to reptiles are unbalanced sex ratios and upward migration [32] [72]. There have been reports of amphibian population reduction and extinction owing to climate change from various parts of the world [10] [32] [38] [108]. Similar to how different effects on butterflies have been discussed globally [32] [52] [65] [147] [151].

The Himalayan region is the area of the world most susceptible to climate change. According to Xu *et al*. (2009), the rate of temperature increase in the Himalaya is three times that of the rest of the world. Based on statistics Shrestha *et al*. (2012) stated that the temperature of the Himalayas has been rising by 0.06°C year as of late. The Intergovernmental Panel on Climate Change (IPCC) forecasts that by 2050 and 2080, the average annual mean temperature of the Asian land mass will have warmed by around 3°C and 5°C, respectively, with substantially higher rates toward the Tibetan Plateau [32] [96] [153]. The Himalayan region, including Sikkim, is experiencing the effects of climate change in the form of glacial melt, altered sowing and harvesting seasons, decreased crop productivity due to new invasive species and weeds, dried-up springs, shifts in the geographic distribution of species, changes in the species diversity of communities, and the extinction of species [29] [32] [77] [123] [124] [135] [136] [142] [153]. Climate change has made the eastern Himalayan region's forests, wildlife, water sources and agricultural sectors extremely vulnerable [31] [32] [111] [142].

2. Material and Methods

The topic of “impact of climate change on herpetofauna” was the subject of a systematic review using “Google Scholar,” a web-based search engine which provides a quick and easy way to search and access published literature from articles, journals and books. Thematic search terms such as impact, climate change and herpetofauna were used in the search.

The subjects that were evaluated in this research were chosen using an approach that involved assessing at the related works of literature. Publications between the years 2000 to 2023 were acquired for this review. However, not all of the articles that were reviewed, were used in this study because the major objective was to assemble data from recent research (past 10 to 20 years) on impact of climate change on herpetofauna. However, papers that contained relevant literature from as far back as the 1900’s and the 2000’s were also utilized for this review. Forty (40) research articles were included in this review.

The search yielded different results: Some articles had all the thematic keywords and some were obtained that were specific to conservation measures to protect herpetofauna, while others were specific on the effect of temperature, precipitation, synergistic vulnerabilities, ultraviolet radiation on herpetofauna and also, repercussions of ectotherm metabolic rate.

3. Results

When searching "Google Scholar" for information on impact of climate change on herpetofauna, a total of 314,000 was retrieved. Among the results obtained from the search, a total of 2,240 were published within the years 2000-2023, 2,250 were published between the years 2010-2023 and 2,270 were published within the years 2015-2023. 2,210 publications between the years 2010-2023 reviewed the impact of climate change on herpetofauna.

However, not all the results retrieved for this research focused on the impact of climate change on herpetofauna. While some focused solely on climate change on herpetofauna, others examined possible conservation measures to protect herpetofauna from the impact of climate change and some were specific on the effect of temperature, precipitation, synergistic vulnerabilities, ultraviolet radiation on herpetofauna and also, repercussions of ectotherm metabolic rate. Further, some papers focused on annotated checklists of herpetofauna, global protected areas as refuges for amphibians and reptiles under climate change and others on the effect of climate change on the potential distribution.

4. Discussion

4.1. Major climatic factors affecting herpetofauna

4.1.1. Temperature

Temperature increases can cause changes in water regulation, oxygen intake, emergence, mating, development, metamorphosis, growth, and sex reversal in amphibians [20] [48]. Many studies have demonstrated that greater temperature can speed the growth rate of embryos and larvae by directly raising development rate or by increasing desiccation of larval habitats, resulting in accelerated development [7] [20] [83] [115]. This can result in early emergence from aquatic habitats, which can minimize aquatic predation, but it can also result in lower size and mass [37], which increases post-metamorphic predation and affects lifelong fitness [15] [20] [128].

Due to inter and intra-specific variance in thermal tolerances, global temperature changes will also affect amphibians and reptiles in subtle or little-known ways. Most lowland tropical herpetofauna die at temperatures between 38 and 42 degrees Celsius, while highland species have lower thermal tolerances [20] [22] [132]. However, most ectotherms do not work well at the upper end of their thermal tolerance, but rather at a lower temperature known as the thermal optimum [20] [48]. Although projected temperature rises are unlikely to approach critical thermal maxima, thermal optima will almost certainly be exceeded for most species due to the small thermal safety margin, and any increase beyond that will have detrimental impacts and impair overall fitness. Temperature fluctuations may also have an effect on amphibian mating success because the frequency of mating calls is directly regulated by temperature [20] [55].

Increased ambient temperatures will also limit the amount of dissolved oxygen in freshwater while raising the metabolic requirement for oxygen in aquatic creatures. Tadpoles must absorb all of their oxygen from water until they reach developmental stage 25 [20] [57] [89]. With less dissolved oxygen available, swimming and evasion performance will suffer, and mortality of juvenile tadpoles would rise [20] [149]. Once tadpoles begin breathing air, they must either increase their oxygen intake from the water's surface or reduce their oxygen demand by limiting activity or development [20].

Temperature increases can have an effect on the sex ratios of reptiles and, to a lesser extent, amphibians. Many reptiles' sexes are determined by egg incubation temperature (TSD), with temperature increases of 2-4 degrees Celsius resulting in all female offspring [36] [46] [72] or all male offspring [24] [33] [106] in crocodilians, turtles, and some lizards. Even in snakes and amphibians, which are normally non-TSD taxa, high temperatures during incubation can alter sex ratios [20] [25] [44] [93] [125]. Although there is little data on TSD, amphibians and reptiles, rising temperatures in the region are anticipated to result in strongly female-skewed populations in many reptiles and some amphibians. Females choosing cooler nest sites to modify offspring sex ratios may mitigate the effects of ambient temperature increases [5] [20] [43] [47] [138], but behavioral changes are unlikely to fully offset the effects of climate change [138]. As a result, all reptiles and certain amphibians are at risk of becoming single-sex populations within the next 100 years [20].

Temperature rises are also expected to change amphibian and reptile ranges. Species may seek cooler microhabitats in their existing range or colder temperatures at higher altitudes, resulting in lowland biotic attrition [19]. Some amphibian species have already been shifted upwards in elevation over the last 30 years [112]. In Southeast Asia, at least nine lowland amphibian species have relocated 500 m or more upward in elevation over the last 70 years, whereas many high elevation species have shifted down slope [20]. This seemingly paradoxical pattern could be the result of increasing ultraviolet B (UV-B) radiation and fewer clouds at higher altitudes, causing amphibians from high elevations without canopy and cloud cover to descend the slope in search of shelter and moisture. This sandwiching of amphibians at mid-level elevations may result in increased competition, smaller population sizes, and changes to assemblages and community structure, eventually reducing biodiversity. Although there is likely to be an increase in species richness at these elevations initially due to range shifts, limiting resources will likely result in changes in community composition, with weaker competitors being extirpated [20].

4.1.2. Precipitation

Precipitation has varied effects for reptiles and amphibians, with reptiles being more acclimated to dry environments than amphibians. Although rainfall and cloud cover will vary widely geographically, many regions will become drier and relatively few will become wetter. Overall, however, precipitation will be more variable, with rainfall episodes spreading further between at one extreme and increasing more intense at the other [20] [70].

Reduced precipitation in South East (SE) Asia has one of the most evident and immediate effects on herpetofauna, namely a loss in breeding cues and viable breeding locations for amphibians. Many species require rainfall to stimulate mating as well as appropriate water for tadpole survival. Increased rainfall variability, for example, will impact the availability of breeding grounds for frogs in the genus *Meristogenys*, which only breed in fast-flowing streams [20] [42]. The drier climates predicted for SE Asia may result in lower stream flow and a population loss of species that require fast flowing water. Furthermore, species with direct development (e.g., *Philautus* species) may suffer greater mortality as a result of drier, warmer temperatures. With reduced precipitation or prolonged droughts, eggs and tadpoles are sensitive to desiccation [20] [42].

Prolonged droughts may also cause reproductive failure in successive years, resulting in population crashes in many species. *Polypedates leucomystax* and *Microhyla heymonsi*, two common protracted breeders, may be the hardest hit because they are habituated to reproducing over lengthy periods of time and may require longer hydroperiods for tadpoles to reach metamorphosis. Amphibians and reptiles will have additional obstacles in the Philippines, which is anticipated to get wetter. Because eggs and tadpoles are more likely to be carried away or injured by stronger torrents, heavier precipitation may result in higher mortality of amphibians that reproduce in slow-moving water. Similarly, mortality rates of reptiles and amphibians that lay their eggs on land may rise as a result of nest flooding and increased fungal development on eggs [20] [66] [76].

Changes in precipitation will also have an indirect influence on reptiles through food supply and habitat [11] [20] and may result in a reduction in body size, growth rate, and lifetime fitness [20] [23] [82]. Color polymorphism can be influenced by higher temperatures and lower humidity [20] [62], which may alter ability to escape predators and capture prey. Furthermore, visual sensitivity may be reduced [3] [20], making it difficult to spot predators and seek food and mates.

As the environment dries out, people may gravitate toward water sources [19]. This increased density of people near damp microhabitats may raise competition and encourage disease vectors, potentially shrinking population sizes. Temperature increases caused by climate change will increase water requirements in amphibians and reptiles. Furthermore, because water is required for many metabolic activities, increased metabolic rates linked with higher temperatures will increase water requirements. Increased temperatures cause more evaporation, requiring amphibians and, to a lesser extent, reptiles to increase their water intake [20].

Climates are anticipated to become drier in all parts of Southeast Asia except the Philippines, and droughts are expected to become more frequent, longer, and more severe. As a result, amphibians and reptiles will have a more difficult time satisfying their water needs since water bodies would be fewer, smaller, and farther apart [20] [42]. This may also result in considerable habitat loss for most non-marine turtles, as well as population size reductions. Furthermore, shorter hydroperiods may result in a decrease in the percentage of males in a given population of frogs that reproduce in ponds or puddles, resulting in less genetic variety in the population [20] [42].

4.1.3. Synergistic vulnerabilities

Increased drought frequency and duration, combined with rising temperatures and fragmentation, are anticipated to make forests drier and more fire prone [20] [94]. The consequences (micro-climate changes, increased nutrient availability, and increased vulnerability to more fires) have been recorded in the Americas [20] [78] [87] [94], but not in Southeast Asia [20] [146]. The majority of Southeast Asian amphibians and reptiles have not co-evolved with a fire regime ecosystem; hence mortality will be substantial in a higher fire scenario. If the 1997-1998 El Nino Southern Oscillation (ENSO) event is any guide, the region is especially vulnerable to synergy swirling around and leading to fires. Except for increased precipitation in the Philippines, the majority of the region would experience climate change consequences that will exacerbate the tendency for fires. The loss of forest cover due to fire can also cause soil erosion, which increases stream sedimentation. Furthermore, eutrophication can occur and harm water quality, impacting amphibians that reproduce in certain areas [20] [59] [103]. These diverse effects may interact synergistically, amplifying the negative consequences on amphibian and reptile populations.

Warmer temperatures and less precipitation will drive fossorial taxa like *Glyphoglossus*, *Calamaria*, *Gastrophrynoides*, *Ichthyophis*, and *Caluella* to burrow deeper into the soil to find sufficient moisture. Many Megophryids and Microhylids that deposit their eggs on land may die as a result of decreasing soil moisture and increased evaporation in drier, warmer conditions. Similarly, canopy dwellers (for example, direct-developing microhylid frogs from New Guinea in the genera *Cophixalus* and *Albericus*) would leave the treetops as they become desiccated and inhospitable [19] [20]. As these arboreal taxa come into touch with species on the ground, they may fight for food and clash with species occupying comparable niches on the ground for breeding sites if those canopy habitats remain unsuitable for egg-laying [20].

Because environmental temperature is known to influence disease resistance, it is anticipated that climate change will have a synergistic effect on both reptile and amphibian pathogen resistance [20] [27] [113]. Amphibians are a good example of this. The lowlands of Southeast Asia are generally too dry or too hot for the survival of the chytrid fungus (*Batrachochytrium dendrobatidis*), which has been linked to massive declines and extinctions of amphibian species in other parts of the world [20] [39] [108] [130]. However, the chytrid fungus can live in environments with higher moisture levels and cooler temperatures (for example, alpine areas above 1000 m elevation). This fungus was recently discovered among native frogs in Mount Gede Pangrango National Park, Indonesia [20] [77], and it has the potential to expand upward in elevation with global warming.

Many reptilian and amphibian populations will decline due to the high likelihood of food scarcity. Even if net primary productivity (NPP) does not change and it almost certainly will [34], organisms will have lower assimilation efficiencies as they deal with water limitations and smaller amounts of biomass at each trophic level, resulting in smaller population sizes. Because NPP is anticipated to drop in the humid tropics [20] [34], biomass at each trophic level will be significantly lower, and population crashes for many species, particularly top predators like Komodo dragons and pythons. As predator populations decline, trophic cascades and the loss of ecosystem functions [20] [104] become visible issues. Furthermore, when body sizes fall, population sizes shrink as well, because many amphibians and reptiles have a direct relationship between body size and number of eggs per clutch [12] [20] [88] [137]. Smaller females produce fewer eggs, which might result in smaller populations.

Predatory reptiles will surely be influenced by prey species numbers or population shifts. Snakes are very sensitive to prey density [20] [85] [86] [126], and their responses to climate change will be due to temperature effects on physiological processes as well as indirect synergistic effects with habitat loss causing local extinction and migration of their prey base. This, like many other synergistic effects for reptiles and amphibians, will have population and species-level consequences.

The hyper-fragmented character of Southeast Asia's remaining pristine habitats—literally, islands on islands—as well as the relatively tiny sizes of many populations amplify clear synergy of temperature, rainfall, UV, cloud cover, fires, and habitat degradation. Some, but not many, of these will be amphibian and reptile-specific issues and weaknesses. The effects of having an ectothermic metabolism that is directly linked to ambient temperatures are foremost among them [20].

4.1.4. Repercussions of ectotherm metabolic rate

Ectotherms' basal metabolic rate is directly related to the temperature of their surroundings. Amphibian and reptile metabolic rates will increase by 10-75% if global temperatures rise by 1.1-6.4 degrees Celsius by 2100 [70]. Caloric intake (food consumption) must rise to maintain mean body size at greater metabolic rates. However, food resources are limited, and hence a population will likely support either a lesser number of individuals or a population size that is 12-53% smaller. To retain their current physical size, animals may need to consume significantly more prey, which may be challenging, if not impossible. Reduced body size has already been observed in birds [54], sheep [100], and aquatic ectotherms [40].

If NPP declines in the humid tropics as predicted [34], biomass at each trophic level will decline even more, potentially causing population crashes of most amphibian and reptile species, as well as other top predators, and leading to a trophic cascade and loss of ecosystem function [20] [104]. Individual organism behavior can influence or offset some daily or seasonal temperature changes, but long-term and overall climate warming will not be properly addressed unless it involves long-distance migration to higher latitudes or elevations. Amphibians and reptiles are becoming more widespread as the temperature changes [20].

In addition to diminishing populations or individuals, increasing metabolic rates caused by rising ambient temperatures can be detrimental to fitness. Females with lower fecundity as a result of greater ambient temperatures will contribute to population decreases. Furthermore, elevated metabolic rates frequently use energy that would otherwise be used for maintenance [20] [51] [120], increasing vulnerability to disease [20] [108]. Increased metabolic rates, which result in an increased surface area to volume ratio, would further threaten the survival of amphibians and many small fossorial reptiles. This ratio will increase by 14% when ambient temperatures rise, exacerbating drying risk on a similar magnitude. Given that temperature increases will speed evaporative water loss in amphibians and small fossorial reptiles [20] [133], the danger of desiccation will be greater than that expected from decreased body size or increased temperature alone. As a result, these taxa will be forced to stay closer to water sources, limiting their ability to disperse. This might cause population clumping and potentially enhance disease propagation, resulting in mass death [20] [42] [108].

4.1.5. Ultraviolet radiation

Increased UV-B exposure causes increased mortality [140], developmental and physiological abnormalities [114], decreased growth rate [18], epithelial damage [92], impaired vision [50], and altered behavior [74] in tadpoles. Numerous substances (pathogens, heavy metals, and chemical pollutants) have been shown to interact synergistically with UV-B, resulting in substantially higher effects than would be expected from the additive effects of individual components [63]. Montane species in Southeast Asia are anticipated to be especially vulnerable to such effects, as decreasing cloud cover results in increased UV-B penetration through the atmosphere [20] [26] [28] [45].

4.1.6. Impact of Climate Change on Various Taxa

Field-based observation showed that different species are affected by climate change in important and measurable ways. In temperate and tropical climates, it has noticeable effects on the plants, butterflies, herpetofauna, birds, and mammals. Empirical evidence and computer models indicate that the main drivers of these effects are changes in temperature at higher elevations and different rainfall patterns at lower elevations [32] [121]. Changes in the timing of biological behaviors like flowering, fruiting, and reproduction, changes in community composition, ecological interaction and community dynamics, and changes in ecosystem function and services are the most noticeable effects of climate change. However, throughout millions of years, a number of species have evolved to adapt to certain climatic circumstances as well as climatic change. The pace of climate change has been so rapid in recent years, many species have been driven to extinction as a result of their inability to adapt quickly [32] [54] [73] [108].

4.1.7. Effect of Climate Change on Herpetofauna

Integrating the higher vertebrates with the lower vertebrates and the terrestrial ecology with the aquatic ecosystem, herpetofauna play a significant role in our ecosystem [20] [32]. Despite being ecologically diversified and playing a significant role in trophic dynamics, herpetofauna are typically not given enough consideration when planning or managing an ecosystem. They are more vulnerable to climate change than other vertebrates because of their ectothermic nature.

4.1.8. Effect of Climate Change on Reptiles

Many reptiles are extremely susceptible to temperature changes caused by climate change due to their ectothermy, which requires them to rely on ambient environmental temperatures to maintain vital physiological processes. Because of the diversity of snakes, lizards, crocodilians, and turtles in our world (traditionally classified as reptiles), and because climate change data and projections vary by location, it will be necessary to consider each species and location separately when considering the potential effects of altered climate on these animals [98].

Lizards are predicted to be quite vulnerable to climate change in temperate zones [11] [68] [91] [98] [129] [145] [154] [155]. Their reproduction is intimately linked to brief periods in the spring and summer when adequate temperature and moisture regimes are available for crucial natural history events like feeding and mating. Changes in weather patterns during these seasons may result in recurrent "bust" years of reproductive failure. Other climate effects on lizard survival include mortality linked with winter warm spells [4] [98], interaction effects of changing vegetation communities, fire regimes, and invasive species [95] [98], and possibly disease [98] [118]. Snakes are closely related to lizards; thus, same effects may also apply to them. New research, like that of lizards, demonstrates species differences: climatic niche models imply that some rattlesnakes may have narrower ranges [79] [98], whereas rat snakes (belonging to the family Colubridae) have greater activity due to rising night temperatures [98] [150].

Concerns about climate change for turtles and crocodilians are threefold. First, as the climate changes, these largely aquatic species may face changing habitats and increased habitat fragmentation. They share similar problems with amphibians in this regard, such as susceptibility to changes in water availability and temperature characteristics. Second, turtles and alligators have temperature-sensitive sex determination: cooler temperatures may result in only male nests, whereas higher temperatures may result in only female nests. Temperature changes in a given area may alter population sex ratios, thereby impacting future reproduction and, over time, reducing evolutionary fitness [56] [98]. Third, coastal animals such as the American alligator and crocodile are vulnerable to increased storm frequency or intensity induced by rising water temperatures.

Storm surges can displace or drown animals, and salt-water incursion into freshwater environments can dehydrate them [98] [119]. Because the United States is a biodiversity hotspot for turtles and turtle conservation challenges are multifaceted, concern about climate change projections in relation to rare turtle species is a particular concern [98] [99]. Table 1 emphasize on how reptilians have been affected by climate change.

4.1.9. Effect of Climate Change on Amphibians

Due to their very transparent skin and dual way of life, amphibians have the potential to be excellent bio-indicators [16] [32]. According to Donnelly and Crump (1998), frogs' three primary physiological processes—water balance, thermoregulation, and hormonal reproductive control—are all impacted by climate change. The porous characteristics of amphibian skin cause rapid water loss through evaporation, upsetting the body's regular water balance. The presence of moisture also affects amphibian behavior.

As poikilothermic vertebrates, frogs' body physiology is influenced by temperature regulation in a variety of ways, including digestion, oxygen intake, vocalization, emerging from hibernation, development, metamorphosis, and growth [32] [42]. The majority of these processes are intricate and have a domino impact on numerous other bodily processes. Additionally, according to Donnelly & Crump (1998) and Bickford *et al*. (2010), most amphibians can only function at suboptimal temperatures and cannot survive at temperatures that are close to their critical maximums. Similar to humans, frogs' reproductive hormones are influenced by climate change. Gonadotropin-releasing hormone, which is released from the brain and affects gonad activity, regulates reproductive cycles in frogs [17] [32]. While there are many factors that can affect amphibian reproduction, rainfall appears to have the greatest impact, especially for tropical species [20]. When rain starts to fall, the hypothalamus receives a cue from the environment and gets ready to start breeding. Table 2 illustrate how amphibians have been affected by climate change.

Table 1 Climate Change and its impact on Reptiles

Effects	Description of impacts	Author(s)
Upward Species Migration	Numerous earlier research mentions the existence of turtles and tortoises in Sikkim, however more recent investigations contradict this. Reptiles are less likely to be impacted by climate change than amphibians are due to their affinity for warmer climates and scaly bodies. Although a warmer climate could seem advantageous in the near term, it has negative long-term effects. The shifting altitudinal and latitudinal limits of species, as seen in other organisms, is one of the important effects of climate change on reptiles. Animals often migrate uphill as a result of seeking protection at higher elevations as the temperature rises. The Sikkim Himalayas have some examples of these migrations. The monocled cobra, *Naja kaouthia*, is a tropical snake that typically lives below 1000 meters, but we have seen it above 1700 meters, clearly demonstrating its upward travel. Western Sikkim has been the site of King Cobra *Ophiophagus hannah* upward progress, according to Bashir *et al*. (2010). Smith (1943) noted that Himalayan Mountain Keelback (*Amphiesma platyceps*) occurs between 1500 and 1800 meters, and Worm Snake (*Trachischium guentheri*) occurs between 900 and 2100 meters, but a study found that these species exist at their highest levels in North Sikkim at 2600 and 2700 meters, respectively. *Trachischium guentheri* was	(Smith 1943); (Waltner 1973); (Henle *et al*. 2008); (Bickford *et al*. 2010); (Acharya & Chetteri, 2012); (Dayananda *et al*., 2021)

	frequent above 2100 m, but we never saw it below 1700 m. While there are several accounts of species migrating uphill as a result of rising temperatures, there are also reports of species migrating downward from high to mid-elevation for a number of different reasons. Although species wedged between low and high elevations may initially increase species richness, competition and changed community dynamics may ultimately lead to a loss of biodiversity. To evaluate species' altitudinal migration and the effects of climate change on reptiles, further in-depth research should be done.	
Biased Sex Ratio	The relationship between temperature and reptile reproduction and development is direct. In the majority of reptile species, temperature controls the sexes. In a North American study on painted turtles, a 4°C increase in temperature favored all female progeny, causing a severe gender imbalance that eventually caused a population crash since there were no males available for fertilization. This conclusion is supported by a Sikkim study. A high-altitude snake from Sikkim with a skewed sex ratio (M: F=1:1.6) is called *Trachischium guentheri*. To fully comprehend how climate change affects the sex determination of Himalayan reptile species, more in-depth research is required. According to Fisher (1930), if the cost of producing both sexes is equal, natural selection has always favored equilibrium in the sex ratio (1:1). Females can minimize the impact of a minor rise in ambient temperature by choosing cooler locations for their nests, but this behavioral modification might not be enough to offset the recent climatic change. Therefore, sex ratio deviation caused by global warming can affect the population dynamics of the reptile community.	(Adolph & Porter, 1993); (Janzen, 1994); (Bull, 2008); (Chettri *et al.* 2009); (Bickford *et al.* 2010); (Acharya & Chetteri, 2012); (Dayananda *et al.*, 2021)
Influx of Exotic Species	Exotic species are invading the area as a result of climate change. An influx could cause an imbalance in the interaction between prey and predators, upsetting the entire food chain. As steep geography forms a natural transition to the plains of North Bengal, an unexpected increase in species could occur. Movement of species from lowland to highland occurs as a result of the hills' favorable climate, endangering the region's endemicity and richness. For instance, the rat snake *Ptyas korros* has Indo-Chinese characteristics, while *Ptyas mucosus*, an Oriental species, lives in the plains of West Bengal. Climate change may cause *Ptyas mucosus* to spread into the hills, reducing the size of the native *Ptyas korros*' niche.	(Pianka, 2000); (Chettri & Bhupathy 2007); (Raxworthy *et al.* 2008); (Acharya & Chetteri, 2012); (Dayananda *et al.*, 2021)
Disappearance of Turtles	Despite historical accounts of their prevalence at lower elevations, turtles and tortoises are not found in Sikkim. Despite the fact that there have been sporadic reports of turtle sightings in the local media recently, the presence of turtles in Sikkim cannot be fully ruled out. However, they have not been seen recently within the state's borders. Therefore, the drying of springs and streams in lower elevation is blamed for the loss of turtles. Dryness might have further lowered the turtles' preferred habitat, calling for a location for additional study and verification.	(Smith 1943); (Waltner 1973); (Acharya & Chetteri, 2012); (Dayananda *et al.*, 2021)

Table 2 Climate Change and its impact on Amphibians

Effects	Description of impacts	Author(s)
Advance Breeding	Amphibians get ready to procreate after the start of rain, as was previously mentioned. Some amphibians in started mating earlier than usual due to an unexpected rainfall event or early summer rain. For instance, the Bush Frog (*Philautus* sp.), which typically breeds from May to September, has pushed its breeding season in recent years and now starts in late March or early April. Due to drier and warmer conditions, *Philautus* spp. experience increased mortality as they develop directly. At low and moderate elevations in early April, fully formed tadpoles of *Duttaphrynus* spp. and *Amolops* spp. can be sited. Similar to this, *Paa liebigii* has been reported to lay eggs between July and August, however breeding has started earlier than three months ago (first week of April). Before amphibians finish their	(Beebee 1995); (Donnelly & Crump, 1998); (Bickford *et al.* 2010); (Acharya & Chetteri, 2012)

	metamorphosis, many streams dry up due to the brief and intense occurrence of early rain followed by dry spells. Both eggs and larva are seriously endangered by this erratic rainfall pattern; either they risk being washed away by torrential downpours or they risk drying out before transformation is complete, which would result in widespread mortality. There have been reports of amphibian breeding seasons getting longer in numerous different places. Climate change has also advanced amphibian breeding in the temperate zone.	
Upward Migration of Species along the Elevation Gradient	Many amphibians worldwide have relocated their ranges upward due to rising global warming and climate change patterns. There is no room for higher elevation species to go up as the creatures of lower elevation do, indicating major ecological ramifications that could result in extinctions. A lot of species in Sikkim for example were well recorded above their elevational range. The snow toad, *Scutiger sikkimensis*, was found at an elevation of 4600 meters, which is 1100 meters higher than the elevation at which it is often found. Similar to this, the Common Toad (*Duttaphrynus himalayana*) was seen as high as 3300 m, however historical resources would have indicated that it can reach 2700 m. Comparisons were largely made with Nepal because Sikkim and Darjeeling lacked baseline data. While similar species can be found in the central or western Himalaya, those in the eastern Himalaya are thought to have a smaller range. By increasing their range, generalist species can quickly adapt to climate change. Specialists in nutrition, microhabitat, and temperature, on the other hand, are unable to adapt to climate change. Raxworthy *et al*. (2008) discovered that 30 species of herpetofauna in Madagascar moved uphill on average 19–51 m over the course of a decade as a result of climate change. Robust analysis to demonstrate the upward movement of species along the elevation gradient in Sikkim is awaited due to the lack of long-term data. However, over 50% of respondents noticed that many species in the Khangchendzonga Himalayan Landscape have shifted higher in range.	(Pounds *et al*. 1997); (Schleich & Kastle, 2002); (D'Amen & Bombi, 2009); (Chaudhary *et al*. 2011); (Acharya & Chetteri, 2012)
Elevational Range Limit	According to our latest research, amphibians have a restricted elevational width; approximately 45% of the species have less than 500 m elevational width. Most amphibian species' small elevational range reflects their susceptibility to numerous environmental conditions, which change at a quicker rate along the elevation gradient. Extreme temperatures are more likely to occur near the species' distributional limit, jeopardizing their range extension. As a result, endemic and restricted range species are the most vulnerable to climate change. The disappearance of the golden toad in Costa Rica is an example of vulnerability due to a small distribution limit (10 square kilometers). Species with a wide elevation range, on the other hand, can expand their ranges and so become better colonists.	(Donnelly & Crump 1998); (Pounds *et al*. 2006); (Araújo *et al*. 2008); (Chettri 2010); (Acharya & Chetteri, 2012)
Impact of Disease on Amphibians	The rapid development of fungal diseases is another significant impact of climate change on amphibians, making them more vulnerable than birds and mammals. The most famous vividly colored frogs of Central America (*Atelopus* sp.) were the first terrestrial vertebrates to experience the effects of climate change. In Costa Rica alone, 67 of 110 endemic species were extinct in less than two decades. The high-altitude golden toad of Monteverde, Costa Rica, has become extinct due to the Chytrid fungus, which has spread rapidly due to rising temperatures caused by climate change. The greatest impact of this fungal disease is felt in mid-elevation rather than low and high elevations since the temperature is optimal for fungal development there.	(Stuart *et al*. 2004); (Pounds *et al*. 2006); (Chettri 2010); (Acharya & Chetteri, 2012)
Drying of Spring Affects Amphibian Population	Short bursts of heavy rain followed by a dry winter have caused streams and springs to dry up. Apart from providing services to people, these bodies of water are home to the majority of amphibians. With the current dry periods and spring drying rate, most amphibian reproduction is hampered, resulting in breeding failure and population reduction. More importantly, the drying up of rapid flowing streams is harmful to many Himalayan indigenous species that are accustomed to torrent streams, such as *Paa* sp., *Amolops* spp., and *Megophrys* spp. (locally referred to as 'Paa'). They are restricted to swift streams because to their unique adaption to	(Feder & Burggren 1992); (Araujo *et al*. 2006); Sathaye *et al*. 2006); (Araújo *et al*.,

	rapidly moving waters. The drying of these streams may eventually lead to the extinction of these species. Amphibians are ectothermic, as such, their distribution and ecology are heavily influenced by rainfall and temperature trends; thus, climate change will have a considerable impact on their variety. Most ectotherms do not work well at the top limit of their thermal tolerance but rather do better at lower temperatures, which is referred to as the thermal optimum. Climate change may interact with biotic and abiotic agents such as diseases and infection, high UV radiation, predators, and competition, resulting in the extinction of species on a global scale.	2008); (Bickford *et al*., 2010); (Tambe *et al*., 2011); (TMI-India, 2012); (Acharya & Chetteri, 2012)

5. Conclusion

This review placed emphasis on the impact of climate change on herpetofauna. In the intermediate position of the ecological food chain, herpetofauna species play a vital role in biodiversity conservation. Reptiles play a significant role in most ecosystems' food webs and also function as both predator and prey species. Herbivorous species can be key seed dispersers, especially on islands. Amphibians consume insect pests, which aids agriculture, and they aid in mosquito control, which promotes human health. Due to their moist, permeable skin, amphibians are prone to drought and harmful compounds, making them excellent markers of ecosystem health. Extreme weather conditions such as high temperature, heavy precipitation, synergistic vulnerabilities, ultraviolet radiation and repercussions of ectotherm metabolic rate all play a role in affecting reproduction, distribution and abundance of herpetofauna. Many countries around the world therefore need to improve their management and conservation efforts to protect herpetofauna from becoming endangered and possibly extinct due to the threatening impact of global climate change. More research should be done in relation to climate change on herpetofauna as well as possible mitigation strategies. Many of the published literatures that was reviewed were external to countries outside the neotropics. There is therefore a need for more extensive research in the neotropical realm based on the impact of climate change on herpetofauna as there is a limited and dearth of information in this biodiversity rich region.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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