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A long-term monitoring programme to understand the impact of climate change on terrestrial herpetofauna of India.

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ABSTRACT. **Anthropogenic climate change is likely to have wide ranging impacts on all aspects of life on earth. Among the many challenges posed by climate change, of particular importance to biologists is its impact on biodiversity and its consequences for ecosystems. South Asia harbours a rich diversity of amphibians and reptiles, which are likely to be impacted by changes in temperature and precipitation patterns. Any effort to mitigate the negative impact of climate change on herpetofauna in the region requires critical ecological and biological data, such as species distributions, population dynamics, phenology, thermal biology etc. Measures have to be put in place to monitor the status of species in key biodiversity areas so that detection of climate change impacts can help frame management interventions. The Long-term Ecological Observatories programme on herpetofauna is an initiative to create such a monitoring programme in different parts of India. In this paper, we provide a background to this project and outline an overview and some expected outcomes.**

KEYWORDS. **Climate change, South Asia, Herpetofauna, Ecology, Conservation**

Introduction

Anthropogenic global climate change can no longer be ignored by environmental, ecological, and conservation programmes. Set in motion by the industrial revolution and the growth of the fossil fuel industry, massive amounts of greenhouse gases are still released into the atmosphere. In the last century alone, average global temperatures increased by more than 1.07 °C (NASA 2021, NOAA 2021). The global mean sea level has increased by 0.2 m, with an accelerating trend in the last few decades (Chen et al. 2017). Climate zones over land have generally shifted towards the poles, and warm seasons are on average two days longer every decade since the 1950s. Extreme weather events including heat waves and heavy precipitation have also increased in the same period (Masson-Delmotte et al. 2021). When global climate change interacts with another large-scale crisis, the rapid loss of biodiversity that is now identified as the sixth mass extinction, the consequences are many (Thomas et al. 2004, Wake and Vredenburg 2008, Bellard et al. 2012, Araújo et al. 2013, Ceballos et al. 2015, Urban 2015, Urban et al. 2016, Pecl et al. 2017).

To avoid extinction due to climate change, species may respond in three ways: (a) by moving across space based on changing environmental conditions, (b) by temporally changing states or events, such as life history traits or breeding periods and/or (c) adaptively adjusting physiological and evolutionary responses (Bellard et al. 2012). The first of these responses can lead to changes in spatial distribution patterns, range sizes, and range limits of species. For example, northward range shifts in many temperate taxa (Parmesan 2006, Duan et al. 2016), and upward elevation changes in distribution in tropical species due to the strong temperature gradient that exists in many tropical mountain ranges (Colwell et al. 2008, Bickford et al. 2010, Menéndez et al. 2014, Kusrini et al. 2017). The second type of response, temporal changes in states or events, can lead to changes in activity patterns, phenology, dispersal, migration, etc. Many species rely on environmental cues such as rainfall to time their life-history attributes, such as metamorphosis, breeding, number of offspring produced etc. Adaptive changes in temporal activity patterns, either seasonal or daily, will be necessary for many species. The third type of response, termed 'self' by Bellard et al (2012) includes physiological and genetic changes that can lead to changes in the biology of the species, such as thermal responses and strategies, or preference of food or microhabitat (Williams et al. 2008). For example, within a population, selection for a particular allele that influences higher thermal tolerance may happen, leading to rapid microevolution. Failing to respond adaptively along any of these three pathways may lead a species to reduction in populations, ultimately leading to either population or species extinction (Bellard et al. 2012, Thurman et al. 2020). The speed with which current climate change is occurring makes it unlikely that many species will evolve adaptations in time. Additionally, our knowledge of the biology and ecology of majority of species is so incomplete that we cannot predict with confidence the number of affected species and the consequences for ecosystems.

In this paper, we provide a broad introduction to the impact of climate change on herpetofauna globally, and review knowledge of impacts on these taxa in South Asia. We then introduce the Long-Term Ecological Observatories programme, and outline our rationale and approach to establishing long-term monitoring for herpetofauna in India. We conclude by encouraging other researchers to take up similar efforts so that we collectively fill the gaps in our knowledge and work to conserve the herpetofaunal diversity of this ancient landscape.

Herpetofauna and climate change

There are nearly 20,000 species of extant amphibians and reptiles, with more species added every year (Frost 2022, Uetz et al. 2022). Unfortunately, herpetofauna are also among the most threatened group of vertebrates, with at least 41% percent of amphibians and 21% of reptiles considered threatened (Green 1997, Gibbons et al. 2000, Beebee and Griffiths 2005, McCallum 2007, Inger et al. 2009, IUCN 2021). Globally, estimates suggest a minimum extinction rate of nearly 7% for amphibians over the next hundred years (McCallum 2007, Alroy 2015). This is a result of most of the common reasons attributed to biodiversity loss in general: habitat loss and degradation, unsustainable use, infectious diseases, etc (Lips 1998, Daszak et al. 1999, Gibbons et al. 2000, Stuart et al. 2004, McCallum 2007, Nunes et al. 2019). While most of the above have caused local or regional losses of herpetofaunal diversity, global climate change is a large-scale threat that also interacts with all the others, and can have far-reaching effects on the future of herpetofaunal diversity (Thomas et al. 2004, Lopez-Alcaide and Macip-Rios 2011).

Abiotic environmental factors, such as temperature and precipitation, have an enormous influence on the biology of amphibians and reptiles (Vitt and Caldwell 2009). Compared to endotherms, changes in the predicted distribution of ectotherms, such as amphibians and reptiles, more closely track the changes in temperature across the globe (Aragón et al. 2010). Thermal biology constrains herpetofauna to limited environmental conditions, though species can respond with behavioural strategies to maintain optimal or preferred thermal conditions (Angilletta 2009). With increasing temperatures, many herpetofauna are expected to face restricted activity windows and considerable physiological costs (Clusella-Trullas and Chown 2011). For tropical herpetofauna, this is an even greater problem as thermal tolerance ranges are already narrow and many species already function at the upper part of their preferred thermal ranges (Huey et al. 2012, Griffis-Kyle et al. 2018). Changes in intensity and timing of precipitation can affect many amphibians that synchronize their breeding activities with specific weather conditions (Blaustein et al. 2010). Changes in temperature and precipitation patterns can alter vegetation type, structure, composition, availability of both food and shelter, and predator-prey/parasite-host dynamics for many species (Parmesan 2006, Blaustein et al. 2010, Bastille-Rousseau et al. 2018). There is some evidence that increase in temperature can reduce the resistance of amphibians to the fungal pathogen *Batrachochytrium dendrobatidis* (also called Bd fungus) which is currently considered one of the leading causes of amphibian extinctions (Raffel et al. 2013). The response of herpetofauna to such changes could be along any of the previously mentioned pathways: 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) (Blaustein et al. 2010, Griffis-Kyle et al. 2018).

South Asian herpetofauna and the threat of climate change

The tropical regions of the world have the highest diversity of herpetofauna, with a large majority of all known species occurring in the Neotropics, West Africa, Southeast Asia, and South Asia. These also include some of the most populous regions in the world. India, the second most populous country in the world, hosts four of the world's biodiversity hotspots: The Western Ghats – Sri Lanka hotspot, the Himalayas, the Indo-Burma hotspot (including parts of Northeast India and the Andaman Islands), and the Sundaland hotspot (including the Nicobar Islands) (Mittermeier et al. 2011). These regions are also amphibian and reptile biodiversity hotspots with more species discovered on a regular basis (e.g. Agarwal et al. 2014, Vijayakumar et al. 2014, Pal et al. 2021, Garg et al. 2021). These hotspots host a significant number of highly threatened, yet largely understudied herpetofauna. For example, more than 35% of amphibian species from the Western Ghats are considered Critically Endangered or Endangered, while a further 45% are Data Deficient or were not assessed for their conservation status (IUCN 2021). The latest assessment by IUCN suggests that among the 107 globally threatened Indian species of reptiles, 12 species are affected due to climate change and severe weather-related causes such as climate change mediated habitat shifting and alterations, droughts, temperature extremes, storms, flooding, and other impacts (IUCN 2021). Since a majority of species from this region lack data on population size, distribution, and other aspects of biology, these assessments are arrived at based largely on expert opinion on commonness or rarity of species, its current distribution, and observed as well as perceived threats. Data based assessments of vulnerability or adaptability to changing climate is not available for of most species.

With some of the highest human densities in the world coexisting with rich biota in South Asia, it is essential to consider these aspects when planning biodiversity conservation. Even conservative estimates suggest an increase of 2 °C in both mean and maximum temperatures throughout most of south Asia in the next fifty years or so (Iturbide et al. 2021, Masson-Delmotte et al. 2021). Days when maximum temperature rises above 35 °C could see an increase to 18 – 48 days, with more hot days in the southern and western regions (Masson-Delmotte et al. 2021). The south-west monsoon, which provides most of the rainfall to a large part of South Asia, is set to increase in the amount of rainfall, but with changes in intensity and timings (Katzenberger et al. 2021). The Himalayas are highly susceptible to adverse effects of global climate change, as the rate of increase in average temperature in the Himalayas is three times the global average (Xu et al. 2009) with a 0.06 °C increase per year (Shrestha et al. 2012). One should expect such changes to create significant fluctuations in local weather patterns also, with direct and indirect impacts on biodiversity throughout the region. However, a review of studies on the impact of climate change on herpetofauna across the world from 2005 to 2015 found no quantitative studies from this entire region (Winter et al. 2016). Instead, more than 70% of all studies pertained to North America and Europe. Addressing this major disparity in the distribution of diversity and information should be a priority in efforts to put the brakes on the biodiversity crisis.

Current knowledge of climate change effects on Indian herpetofauna

Generally, there is a dearth of long-term ecological studies on amphibians and reptiles (other than Chelonians and Crocodilians) in south Asia. This is not to discount short-term studies on aspects of natural history and ecology, which are foundational. Among reptiles, extreme temperatures may affect sex ratios due to Temperature mediated Sex Determination (TSD) (Pezaro et al. 2017). Higher incubation temperatures result in producing more females in turtles and more males in crocodilians, both of which can affect long-term population survival (Lang and Andrews 1994, Valenzuela et al. 2019). Large-scale studies, such as those spanning the range of a species, or a landscape, or studies that span multiple generations are generally missing for most amphibians and squamate reptiles. Tackling the problem of climate change impact on biodiversity requires baseline information on distribution and population status, which is lacking for majority of Indian species. This information has to be combined with long-term ecological monitoring to detect changes and identify thresholds at which management intervention might be necessary.

Since the publication of the Winter et al. (2016) paper, there have been a few studies examining the potential impact of climate change on herpetofauna in this region (Srinivasulu and Srinivasulu 2016, Subba et al. 2018, Srinivasulu et al. 2021). Range shifts to higher elevations by low elevation herpetofauna have been reported for several species in the Himalayas (Acharya and Chettri 2012). This study also recorded changes in breeding seasonality of two amphibian species. Four species of Himalayan amphibians are expected to reduce their geographic distributions, indicating increased extinction risk (Subba et al. 2018). Habitat suitability models in conjunction with future climate models predict several endemic herpetofauna of southern India to shrink or shift their geographic ranges in response to increasing temperatures, with up to 73.48% reduction in climatically suitable habitat for some species by the year 2050 (Srinivasulu and Srinivasulu 2016, Srinivasulu et al. 2021). It should be noted that these studies analysed a single pathway of potential impact and response – potential changes in future climate suitability using current occurrence data – and cover less than 5% of all the species found in this region. Only one study (Subba et al. 2018) examined potential species migration scenarios, the likelihood of which can vary according to the nature of available habitats and other anthropogenic pressures. Species may respond to climate change and associated impacts through other response pathways. Therefore, depending on the specific scenarios, the chances of extinction may be lower or higher than that indicated by these studies. Therein lays a large space for studies, both local and regional, to fill information gaps, monitor status, and create better quantitative predictions of species responses to current and future threats.

The Long-Term Ecological Observatories programme in India

Long-term studies targeting amphibians and reptiles are rare in general. Some of the more well-known, organized programmes that covered large areas include the 'North American Amphibian Monitoring Program' (NAAMP) (https://www.usgs.gov/centers/eesc/science/north-american-amphibian-monitoring-program), 'Amphibian Research and Monitoring Initiative' (ARMI) (https://armi.usgs.gov), and the United Kingdom's National Amphibian and Reptile Monitoring Programme (https://monitoring.arc-trust.org). There are a few other somewhat long-term studies that focused on a species or a small region, such as the 11-year mark-recapture study of boreal toads (*Bufo boreas*) in Colorado, and the 31-year study of

Coachella Fringe-toed Lizards (*Uma inornata*) (Scherer et al. 2005, Fisher et al. 2020). However, almost all such efforts are in North America and Europe. To support effective climate change mitigation and biodiversity conservation, South Asia needs far more effort in large-scale and long-term projects.

The urgent need to understand climate change impacts was the main driver behind the launch of the 'Indian Long-Term Ecological Observatories' programme (https://lteo.iisc.ac.in/research/herpertofauna/) by India's Ministry of Environment, Forest and Climate Change (MoEF&CC), which envisioned an extensive network of biodiversity monitoring programmes spread across India (ILTEO, 2015). Under this umbrella project, there are multiple themes and groups working towards the common goal of understanding the effect of global climate change on India's biodiversity. For the first phase of the project, six regions representative of the biogeographic diversity of India were selected for establishment of long-term ecological observatories. These are North-west Arid Zone (NWAZ), Western Himalayas (WH), Eastern Himalayas (EH), Central Indian Forests (CI), Western Ghats (WG), and Andaman Islands (ANI). The herpetofauna group is a multi-institutional partnership (Fig. 1)

Establishing a Long term herpetofaunal monitoring programme in India

The LTEO herpetofauna programme has three major objectives. The first is the establishment of monitoring sites and standardization of protocols. The LTEO monitoring programme will use spatial environmental gradients to understand the effects of environmental and climatic variables on distribution, abundance, thermal adaptation, and phenology of herpetofauna in six regions. In three regions, viz. WH, EH, and WG, monitoring will be along elevation gradients. Both WH and EH are part of the Himalayan Mountain range, and are characterized by extreme elevation gradients, though for the pur-

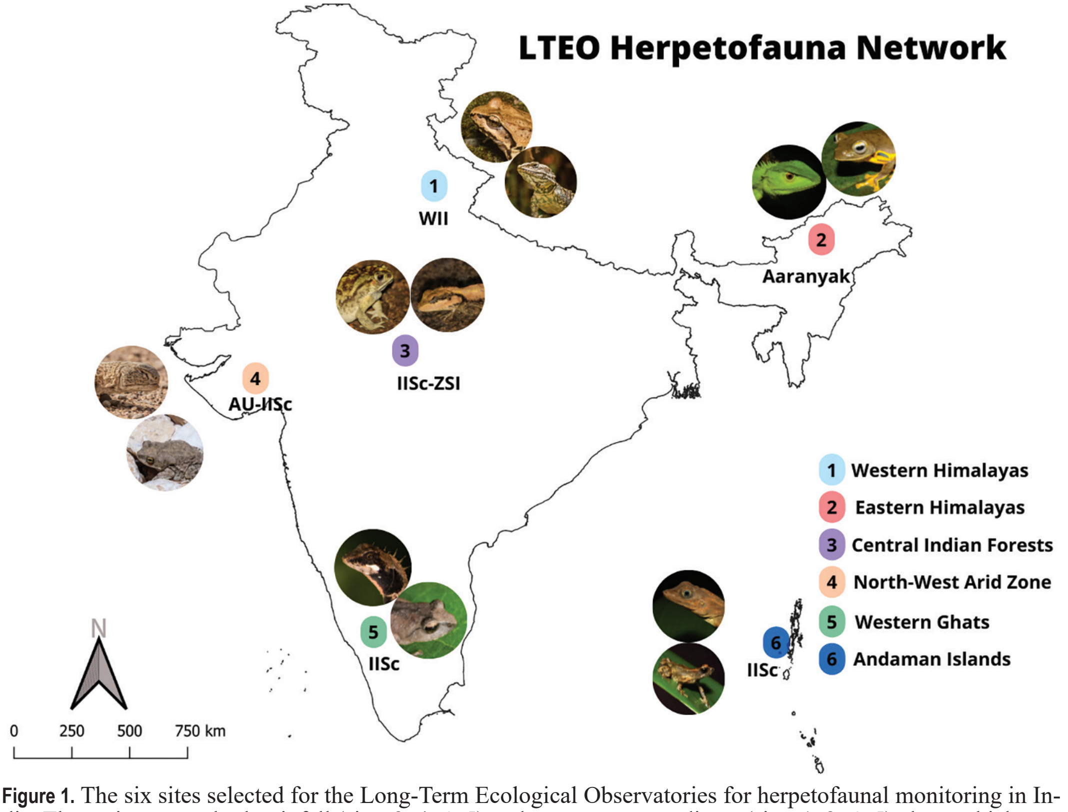

Figure 1. The six sites selected for the Long-Term Ecological Observatories for herpetofaunal monitoring in India. These sites cover both rainfall (sites 3, 4, & 5) and temperature gradients (sites 1, 2, & 5) along which representative species of amphibians and reptiles will be monitored. Institutional abbreviations are: WII – Wildlife Institute of India, Dehra Dun, Aaranyak – Aaranyak, Guwahati, ZSI – Zoological Survey of India, Kolkata, AU – Ahmedabad University, Ahmedabad, IISc – Indian Institute of Science, Bengaluru.

pose of herpetofaunal monitoring, sampling will be largely restricted to elevations below 3500 m above sea level (asl). The WG is a mountain chain running along the southwest coast of India. The region chosen for the LTEO sites fall in the Nilgiri-Wayanad region, having an elevation gradient between 500 to 2500 m asl.

In two other regions, viz., NWAZ and CIF, the monitoring will be along a rainfall gradient, in a west-southwest to northeast direction. This includes arid zones in the western part of India in the state of Gujarat and Rajasthan, with average annual rainfall ranging from 185 mm in the arid regions in the west to 2000 mm in the CIF. The ANI is a chain of islands in the Bay of Bengal. ANI has high average annual rainfall (over 3000 mm) and relatively warm, relatively stable temperature (20–35 °C) throughout the year. Since there are no major climatic gradients in ANI, monitoring will focus on long-term ecological changes in a few selected sites. We selected these sites based on representative vegetation for the region, level of anthropogenic disturbance, and ease of access for long-term, repeated sampling.

The second, and long-term, objective of the monitoring programme is to predict and detect changes in herpetofaunal communities, such as range shifts and changes in relative abundance, in response to climate change. There is limited information available on commonness and rarity of species in the regions under consideration, as well as on efficiency of various sampling methods. Therefore, we plan to start by using a community or guild-based approach to sampling. The short-term objective is therefore the collection of preliminary data and standardization of sampling/monitoring methods across the regions. We will collect data on occurrence of species, abundance, species richness, and a number of environmental covariates at each of the monitoring sites.

The primary requirement for detecting range shift along elevation gradient is mapping the upper and lower range limits as well as a measure of abundance. Often, a lowering of abundance at the range boundary is the first sign of range shifts. Therefore, early detection of range shifts will require detecting changes in abundance as well. The sampling strategy adopted should therefore be able to detect changes in occurrence as well as abundance over several years. Considering the logistic and analytical difficulties in estimating abundance of amphibians and reptiles, using site occupancy is the best choice for detecting changes over several years (MacKenzie et al. 2002, Mackenzie 2005, Muths et al. 2012, Adams et al. 2013, Grant et al. 2016). In the absence of initial estimates of occupancy and detection probabilities, we cannot derive objective estimates of the number of sites and surveys necessary for the most efficient survey design (Mackenzie and Royle 2005). Therefore, the goal of preliminary surveys in the first year will be to document species occurrence and relative abundance in the study sites through repeated sampling. We will use these results to refine the study design further in terms of focal taxa, number of sites, and sampling occasions.

In five of the six regions, we have identified transects along elevation and rainfall gradients, divided into minimum three strata (low, medium, and high). The survey locations within strata will be of dimensions 2 km x 2 km, consisting of 100 m × 100 m grids at each stratum. The general survey method used will be Visual Encounter Surveys (VES) in combination with acoustic surveys (Crump and Scott Jr 1994). VES yields the highest number of species and individuals for a given survey effort, while creating the least amount of disturbance to the habitat (Doan 2003). This makes the method repeatable during the same season and year after year. These surveys will provide occurrence, count, and species richness information as well as other biological parameters.

The third major objective of the programme is to understand species adaptations to changing climate. This will include changes in breeding biology, phenology, and thermal adaptations. These will be in the form of species-specific studies in each region, along the environmental gradient. After some preliminary data is collected, we plan to select a subset of species (where feasible) for population monitoring using a mark-recapture framework (Sutherland 2006, Patel and Das 2020). Repeated surveys will also help us collect information of breeding phenology for many species of amphibians. Based on this information, we will select a subset of species representative of the spatio-temporal and ecological space occupied by all species in the region, for long-term monitoring of population and breeding phenology. For understanding thermal adaptations, the primary requirement is capturing the thermal heterogeneity by sampling along the natural environmental gradient (e.g., rainfall or temperature) (Weatherhead et al. 2012, Díaz de la Vega-Pérez et al. 2019). We will collect Operative Temperature data for focal species by use copper models with thermo-loggers along the gradients, capturing as much of the thermal heterogeneity as possible (Angilletta 2009). To obtain body temperatures of animals and surface temperatures of substrates, we will use thermal images of lizards (Goller et al. 2014). LTEO weather station data will provide ambient temperature data.

At the end of preliminary sampling, we expect to have site-specific species lists, estimates of species occupancy along with detection probabilities for at least a subset of species present, and another measure of commonness/rarity of species (abundance or relative abundance) in all regions. During this period, we also expect to generate baseline data on thermal adaptations and breeding phenology of a subset of species. Based on these, we hope to refine long-term monitoring strategy. The six regions selected here are representative of the climatic variation across India. By identifying species, or species groups (based on biology and ecology) that are most vulnerable to changes in climatic factors in these regions, or traits that are common for species across these regions, we hope to extend the findings from these sites to other areas across South Asia. The LTEO programme is an ambitious project seeking to establish a first-of-its-kind ecological monitoring for herpetofauna across India. While the challenges are many, the successful implementation of the project can have immense impact on the conservation of species in this region.

Conclusion

The current climate change crisis is perhaps the most drastic global climatic event that biodiversity has faced since the end of the Pleistocene ice age. Even with a significant reduction in future carbon emissions, the legacy of last two centuries of emissions is likely to have a lingering effect on earth's climate and push global temperatures up for several more decades. Therefore, there is a pressing need to devise mitigation strategies for the detrimental effects of global climate change. For biodiversity, this begins with monitoring changes, predicting species responses, and identifying thresholds for management intervention. The LTEO programme will help us predict and monitor the effects of climate change on herpetofaunal species so that detrimental changes are detected in time for appropriate adaptive management interventions. For example, enhancement and restoration of breeding sites may be necessary for some amphibian species under altered rainfall regimes, while habitat enhancement/manipulations might be necessary for survival of many amphibians and reptiles in hotter environments (Shoo et al. 2011) However, there are still large regions of the country, such as the Eastern Ghats and the coastal plains, and many species that cannot be covered through the current LTEO programme. It is our hope that more researchers will initiate long-term studies on herpetofaunal species across the country, especially in areas not covered by the LTEO programme, so that we can collectively build the knowledge-base necessary to combat the effects of global climate change.

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