Threatened species could be more vulnerable to climate change in tropical countries

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Abstract

Insects are the most speciose group of animals and play a central role in ecosystem processes and functioning, yet they are often overlooked in conservation studies. Many studies have reported a dramatic decline of insects globally, where climate change is considered a profound threat; however, how climate change is impacting tropical insects is largely unknown, given most studies are from the temperate region. Here, by considering Bangladeshi butterflies as a case study, I developed climatic suitability maps for 242 species and compared the suitability under current and future (2081-2100) climatic conditions. Overall, the projected future climate could impact 241 of 242 butterfly species (except for Spindasis elima), where 42% species could experience range contraction. Alarmingly, the impact could be significantly more severe among threatened species. While the direction of shift in habitat suitability could be multidimensional, about 65% of species might move north. While the suitability range could expand for about 58%, most threatened species (58%) could experience range contraction. The mean elevation of the suitable habitat could increase by 238%, and again the situation could be more severe for the threatened butterflies (from 42m to 108m). The niche-overlap analysis indicates that about 54% of the realised niche could be altered. Although there might be no significant association between the shift in habitat suitability along the elevational gradient, migratory species could experience a more significant shift than non-migrants. I show that climate change could have a severe impact on Bangladeshi butterflies – depending on Socio-Economic Pathways (ssps), the future climatic condition could be unsuitable for 2 (ssp126) – 34% (ssp585) species. To mitigate insect decline globally, and therefore, to meet the Post 2020 Biodiversity Framework targets, I urge immediate detection of climate change impact on tropical insects and developing effective conservation strategies.

Introduction

Insects are a megadiverse group comprising an estimated 5.5 million species globally (Stork, 2018). They play a central role in ecosystem processes and functioning through pollination, herbivory, detritivory, nutrient cycling, influencing the physiology and population dynamics of plants, and providing a major food source for species from higher trophic levels (Samways, 2007; Stork, 2018; Wagner, 2020; Dicks et al., 2021; Seibold et al., 2021). Recent studies suggest that insect populations are in a state of catastrophic collapse in many parts of the world, evidenced by rapid declines in abundance as well as extinctions (Hallmann et al., 2017; Didham et al., 2020; Wagner, 2020; Cardoso et al., 2020; Goulson, 2021; Wagner et al., 2021). Yet the extent of the global insect collapse is poorly understood (Wagner, 2020), given that insects comprise only 8% of species formally assessed against IUCN Red List extinction risk criteria (12,100 of 142,577 species; https://www.iucnredlist.org/; accessed on 15 April 2022).

Despite their apparent importance, insects are often neglected in studies on ecosystem function and conservation assessments (Dunn, 2005; Samways, 2007; Di Marco et al., 2017; Taylor et al., 2018; Geyle et al., 2021); however, butterflies, to some extent, are an exception because the taxonomy, geographic distribution and status of many species are relatively well known (Schulze et al., 2004, Schultz et al., 2019). Butterflies are good indicators of habitat quality as well as general environmental health (Dennis et al., 2003), are sensitive to disturbance and changes in their habitat, and can severely be affected by environmental changes, including abiotic factors - such as temperature, light intensity, soil composition, radiation, humidity, photoperiod, and changes in the forest structure (Whitworth et al., 2018). Even minor changes in their habitat can lead to either migration or local extinction (Thomas et al., 2006; Chowdhury et al., 2017). Recent studies have revealed dramatic declines in the richness and abundance of butterflies worldwide, with climate change and habitat alteration emerging as critical threats (Forister et al., 2010; Oliver et al., 2015; Forister et al., 2019; Soroye et al., 2020; Wagner, 2020; Halsch et al., 2021; Hill et al., 2021; Raven and Wagner, 2021).

The world's temperature has risen by ˜ 1°C since 1880 (McGregor, 2018), and precipitation patterns are also changing (Dore, 2005). Climate change substantially impacts species' biological systems, leading to shifts in the timing of important life-history events, changes in geographical distribution and phenotypical features, migration, and even extinction (Walther et al., 2002; Lenoir et al., 2010; Parmesan, 2006; Van der Putten, 2012; Gardner et al., 2011; Lenoir and Svenning, 2014; Furlong and Zalucki, 2017; Oostra et al., 2018; Lindestad et al., 2019; Merckx et al., 2021). In fact, climate change is predicted to become the dominant driver of global species decline in the coming future (Di Marco et al., 2019). With the increasing temperature, species need to move polewards to track suitable environmental conditions and prevent widespread extinction (Thomas et al. 2004), which has been documented in many taxa (Parmesan 1996; Hill et al. 1999; Parmesan et al. 1999; Parmesan & Yohe 2003; Wilson et al. 2005; Hickling et al. 2006; Poyry et al. 2009; Amano et al., 2014; Garcia et al., 2014; Warren et al., 2018). Climate-induced shifts in a species distribution commonly involve movement toward higher latitude (with a median rate of 1.69 km/year) and higher elevation (with a median rate of 1.1 m/year; Chen et al., 2011). Due to several anthropogenic stressors, geographic range shifts required to track changing climate are about 2-5 times higher than the fastest range shifts observed in the fossil record (Davis & Shaw, 2001).

Due to a short lifespan and being sensitive to environmental conditions, butterflies have been widely considered a model group to assess climate change impacts on ecosystems (Dennis et al., 2003; Nadeau et al., 2017). About 29% of studies testing climate change impact on insects are on butterflies (Andrew et al., 2013). Given climate change is a major factor contributing to butterfly decline globally (Wagner, 2020; Halsch et al., 2021), identifying the extent of climate change impact on butterflies is a top conservation priority (Hill et al., 2021). When climate changes, species move areas to match the suitable climate (Thomas et al., 2004). There is mounting evidence showing species redistribution as a response to climate change globally (Chen et al., 2011; Taheri et al., 2021). Species distribution models (SDMs) are widely used to assess climate change impact on species distributions and to forecast changes in distributions under different climate change scenarios (Pearson & Dawson, 2003; Araújo et al., 2005; Heikkinen et al., 2006; Elith et al., 2010; Yates et al., 2010). With SDMs, we can predict the probable abundance of species based on resource distributions or climatic variables (Eskildsen et al., 2013; Araújo et al., 2019). Species with wide and variable distribution and species that have been accidentally or deliberately introduced to a new geographic area and eventually have established and spread fit the model description (Guisan and Zimmermann, 2000, Elith et al., 2006, Elith et al., 2011).

Climate change impact differs markedly both taxonomically and geographically with the temperature (Mikkonen et al., 2015; Amano et al., 2020; Taheri et al., 2021), yet most studies are taxonomically and geographically biased. Of the published literature on insect redistribution as a response to climate change, about 50% are from Europe (only four studies from south Asia) and 23.47% on birds (only 0.44% on insects; Taheri et al., 2021). A vast majority of insect species are distributed in the tropics, yet how climate change impacts tropical insects is largely unknown (Chen et al., 2011; García-Robledo et al., 2020; Kwon et al., 2014; Taheri et al., 2021). Here, I assess climate change impact on butterflies in a tropical country, Bangladesh – a South Asian developing country. Bangladesh is located at the transition between the Indo-Himalayan and Indo-Chinese subregions of the Oriental region (Reza and Hasan, 2019) and forms part of the Indo-Burma biodiversity hotspot (Mittermeier et al., 1998). Being the most densely populated country (among countries with [?]10 million people), there is always a high demand for the limited resources, which is causing rapid habitat clearance, and natural resource extraction is a crucial economic activity (Mukul et al., 2008; Watson et al., 2014; Chowdhury et al., 2021b, f). Only about 11% of the original forest cover in Bangladesh remains, and deforestation is continuing rapidly (Poffenberger, 2000; Mukul and Quazi, 2009; Chowdhury et al., 2021b). About 62% of 305 butterflies found in Bangladesh are now threatened with local extinction (IUCN Bangladesh, 2015).

Here I collate species distribution records from a range of sources (online repository, social media, and published literature), and i) develop climatic niche models for 242 Bangladeshi butterfly species using current and four future climatic scenarios, ii) compare the suitability maps to assess the impact of climate change, iii) develop generalised linear mixed models (GLMMs) to assess if the shift in suitable habitat is associated with the current amount of suitable habitat and elevational distribution, and iv) compare the results between migratory and non-migratory species to determine if migratory species can adjust with the shift faster than the non-migratory species. Finally, I discuss ways to mitigate climate change impact on tropical insects. I chose butterflies as a model group because butterflies are the most threatened assessed taxonomic group in Bangladesh (62% are nationally threatened), the only assessed insect group in the most recent national threatened species assessment (IUCN Bangladesh, 2015; Chowdhury et al., 2021b).

Methods

Data

First, I collected a complete checklist of butterflies of Bangladesh from the most recent national Red List databook (305 species; IUCN Bangladesh, 2015), which contains both threatened and non-threatened butterflies. While collating species distribution data, I followed a range of approaches following Chowdhury et al. (2021a, b). Initially, I downloaded spatial occurrence records from the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/) using the 'rgbif' package (Chamberlain et al., 2017) in R (R version 4.0.4). GBIF is a global data infrastructure network that compiles species occurrence records from several sources, including museum specimens and citizen science projects (Heberling et al., 2021). To avoid repetition, I did not collect data from other biodiversity repositories. Second, I searched for species distribution records in a Facebook group: Butterfly Bangladesh (https://www.facebook.com/groups/488719627817749). Here, I searched by species common name obtained from IUCN Bangladesh (2015), double-checked the identification in each photograph, and georeferenced the observations using the Google Map (https://maps.google.com/). I excluded photographs if the identification was incomplete (not up to species level) or wrong, if the photograph was not clear (from the taxonomic viewpoint), and if the location was unspecified (Chowdhury et al., 2021a, b). Third, I included my personal field observation records. Finally, I scanned for species distribution records from the published resources. Overall, the dataset contained 27,580 spatial records.

I collected both the current and the future (2081-2100) climatic data at 21.625 km2 resolution (2.5 min) from the WorldClim database (https://worldclim.org/). For the future climatic data, I used projections developed by Coupled Model Intercomparison Project (CNRM-CM6-1) in four Shared Socio-Economic Pathways (ssp; ssp126, ssp245, ssp370, and ssp585).

To compare the results between the migratory and the non-migratory butterflies, I downloaded the list of migratory butterflies from Chowdhury et al. (2021d).

Data cleaning

During the spatial data cleaning process, I removed duplicate records, precision uncertainty over 10 km, imprecise coordinates (zero coordinates, integers, records in oceans), and invalid coordinates that the specified locality was incompatible with the coordinates given (Chowdhury et al., 2021a, b, e) using the Coordinate-Cleaner package (Zizka et al., 2019) in R.

To control sampling bias, I followed the spatial thinning approach. Using the spThin R package (Aiello-Lammens et al., 2015), for each butterfly species, I considered occurrence records at 4.65 km distant from each other, which means that there was only a single occurrence record at 21.625 km^2. The final dataset contained 7,606 records for 285 species (Figure 1; supplementary table S1).

Before fitting the model, I checked collinearity among the WorldClim variables and removed highly correlated ($r > 0.75$) variables (Zurell et al., 2020). I removed 11 variables (bio2, bio4, bio5, bio6, bio7, bio8, bio10, bio12, bio13, bio16, bio19) and had 8 variables for the model fitting. I used the same eight variables for future model predictions.

Climatic niche model

I developed MaxEnt climatic niche model in R using the ENMeval package (Muscarella et al., 2014) by considering eight climatic variables. I validated each model with 10-fold cross-validation, tuned it using six feature class combinations ("L", "LQ", "H", "LQH", "LQHP", "LQHPT") and several candidate regularisation multipliers. While choosing the best model, I chose the one with the highest AUC (the Area Under the Curve) score. I used the 'checkerboard2' evaluation method to handle model overinflation resulting from biased sampling (Muscarella et al., 2014; Chowdhury et al., 2021b,e), which partitions both geospatial records and background points into evaluation bins to reduce spatial autocorrelation between points in the testing and training bins (Muscarella et al., 2014). I used the best-fitted model (with the current climatic data) and predicted the future suitability (with the future climatic data) using the 'dismo' R package (Hijmans et al., 2017).

Based on the maximum sum and sensitivity statistics, I did threshold the suitability map (Liu et al.,2016) and converted it into binary (1 (presence): suitability value > threshold; 0 (absence): suitability value [?] threshold). To threshold the future suitability map, I used the same threshold value obtained from the best-fitted model under the current climatic condition. Overall, I obtained five suitability maps (current, ssp126, ssp245, ssp370, and ssp585) for each of the 242 butterfly species.

Changes in suitability distribution

To assess the impact of climate change on the suitability of Bangladeshi butterflies, I followed four steps. First, I calculated the centroid (centre point (latitude and longitude)) and the area (summed the pixel value (1/0) and multiplied it with the pixel resolution (21.625 km2)) for each suitability map using the 'raster' R package (Hijmans et al., 2015). Second, I calculated the distance and angle between the centroids using the 'geosphere' R package (Hijmans, 2017). Third, for each species, I calculated the regions where the suitability range expanded, contracted, or remained the same (overlapped) using the 'raster' R package (Hijmans et al., 2015). I stacked all the rasters (species-wise) to determine the overall expanded, contracted, and overlapped regions. Finally, I calculated the potential change in realised niche distribution between the current and the future suitability distributions using the 'dismo' R package (Hijmans et al., 2017). For all these combinations, I compared the current suitability with the four future climatic scenarios (ssp126, ssp245, ssp370, and ssp585); however, for the clarity purpose, I only used the results of the ssp126 in the main manuscript, and the rest of the results are in the supplementary section. It should be noted that I only measured the climate exposure rather than a full measure of climatic vulnerability, given I did not account for species sensitivity and adaptability to climatic change.

Statistical analysis

To determine if the range shift (centroid distance: distance between the current and future centroids) is associated with the amount of current suitable habitat and elevational distribution, I ran two separate GLMMs in R using the 'glmmTMB' package (Magnusson et al., 2017). To calculate whether the range shift (centroid distance) is associated with the current suitability distribution along the elevational gradient, I added the centroid distance as the response variable and the interaction between mean elevation (current) and migratory status as the explanatory variable. I used the interaction of migratory status with the response variable to account for how migratory species can adjust to the new habitat faster than the non-migratory species and assess if Bangladeshi migratory butterflies follow a similar trend. To calculate whether the range shift is associated with the amount of suitable habitat (current), I ran a similar model considering the range shift as the response variable and the interactive effect of the amount of suitable habitat (current) and species migratory status as the explanatory variable.

In both cases, I used the 'nbinom2' family to account for overdispersion and butterfly families as a random factor. Finally, if any interaction was significant, I conducted post hoc pairwise comparison tests using the 'emmeans' R package (Lenth et al., 2019).

To assess the vulnerability status of the threatened and non-threatened species, I ran two separate GLMMs (for centroid distance and elevation shift) in R using the 'glmmTMB' package (Magnusson et al., 2017). To test whether threatened species experienced more range shift or elevation shift, I added centroid distance and elevation shift periodically as the response variables and the threat status as the explanatory variable. I used the 'nbinom2' family to account for overdispersion and butterfly families as a random factor. Given that there were negative values in the elevation shift (species for which the mean elevation declined), before fitting the model, I transformed the values by adding (1+ maximum negative values) for each species.

Results

I obtained climatic suitability maps for 242 species of Bangladeshi butterflies (80% of 305 species) belonging to all the six major butterfly families (Nymphalidae: 81; Lycaenidae: 66; Hesperiidae: 51; Pieridae: 21; Papilionidae: 19; and Riodinidae: 3 species).

The fitted current and projected future climate suitability varied substantially over Bangladesh (Figure 2). The current suitability peaked in the north-east region, was marginally higher in the centre and some parts of the south-east regions, whereas the suitability was somewhat similar in the other parts and lowest in the north-west and southern parts of Bangladesh (Figure 2a). While the peak suitability of the current and the future distribution could be similar – being highest in the north-east (and east), the future suitability could be evenly distributed across the country, except for some parts of the south-west region (Figure 2b).

For both threatened and non-threatened butterflies, the centroid of the suitability distribution could shift in different directions (Figure 2c). The mean direction of shift in habitat suitability could be 196deg, and for about 65% of species (152 species), the centroid could shift towards the north. There might be no consistent direction of the shift, although, for most species (60 species; threatened: 31, non-threatened: 29), the suitability could shift towards north-north-west (316deg-359deg) directions (Figure 2c). For the threatened butterflies, the shift could occur mostly towards the south-south-east (33 species; 181deg-224deg), north-north-west (31 species), and the north-north-east (24 species; 1deg-44deg) directions, whereas it could be the north-north-west direction for the non-threatened species.

In some directions, I obtained striking differences in the climatic shift between the threatened and non-threatened butterflies. For example, the suitability could shift in the south-south-west direction for 33 threatened but three non-threatened butterfly species (Figure 2c). The centroid shift could be similar in the other directions between the threatened and the non-threatened species.

Overall, compared to the current suitability distribution, there could be marked variation in the suitability distribution of Bangladeshi butterflies in the future climatic scenario (Figure 3). The pixels, for which the suitability might remain the same in the present and the future climatic conditions, would be distributed in the central and the eastern part (north-east, east, and southeast), and there might be no such overlap in most of the northern (mostly north and north-west) and southern (mostly south and south-west) parts of Bangladesh (Figure 3a). The pixels for which the suitability range might expand due to climate change would be distributed along the northeast and southeast, whereas there might be no range expansion in the central part of Bangladesh (Figure 3b). In contrast, pixels for which the suitability range could contract in the future climatic scenario would be primarily distributed in the central, some parts of the north-east and east, and the southeast part of Bangladesh (Figure 3c).

In future, there might be no climatically suitable habitat for six butterfly species currently found in Bangladesh: *Belenois aurota, Ixias pyrene, Junonia orithya, Tajuria cippus, Virachola Isocrates, and Aeromachus stigmata* ; five of these species are currently listed threatened in the national Red List (IUCN Bangladesh, 2015). However, in other climatic scenarios, there might be no suitable climatic habitat for many more species: 38 species (16% species) in ssp245, 59 species (24% species) in ssp370, and 73 species (30% species) in ssp585 (see the supplementary table S2 for more details).

While comparing the centroid shift in habitat suitability among Bangladeshi butterflies, the mean shift was larger for non-threatened butterflies (77km2) than the threatened ones (55km2; Figure 4a). There were 38 threatened butterfly species, for which the range could shift by 100 km, whereas six non-threatened species could experience such a shift (Figure 4a). There might be no change in the centroid location for one butterfly species (*Spindasis elima*), which is non-threatened.

In the future climatic scenario, the amount of suitable habitat could change for 241 (threatened: 153 species; non-threatened: 88 species) Bangladeshi butterfly species, of which 102 species (42% species) could experience contraction and 139 species (58% species) could experience expansion (Figure 4b). The suitable habitat could contract by >10,000 km2 for 64 butterfly species [threatened: 50 species; non-threatened: 14 species] and could expand by >10,000km2 for 116 species [threatened: 44 species, non-threatened: 72 species]. While the suitable habitat might contract for 58% of threatened Bangladeshi butterfly species, 16% of non-threatened species would experience such a situation. When comparing migratory and non-migratory species, the climatically suitable area could increase for most migrants (62%), while the suitability area could decrease for most of the non-migrants (55%; supplementary table S2).

The mean elevation of the suitable habitat for Bangladeshi butterflies could increase by 238% (from 34m to 81m), and the condition could be more severe for the threatened butterflies (from 42m to 108m) than the non-threatened species (from 22m to 34m; Figure 4c). While the mean elevation could increase for 204 species (threatened: 127 species; non-threatened: 77 species), it could decrease for 30 species (threatened: 21 species; non-threatened: 9 species). There might be no change in mean elevation for one species (*Spindasis elima*). There were 25 species for which the mean elevation could increase by >150m, and all these species are threatened (Figure 4c).

The mean overlap of suitable niches in the current and the future climatic condition of Bangladesh butterflies could be 46% (Figure 4d), which means that 54% of suitable habitats could be altered due to climate change. Although the amount of niche overlap could be pretty similar between the threatened and the non-threatened butterfly species, there might be substantial species-wise differences. For 44 species, the niche could shift by >75%, whereas <25% niche shift for 23 species (Figure 4d).

Overall, there might be no significant effect of species elevational distribution ($\chi2 = 0.0306$, df = 1, p-value = 0.8611) and migratory status ($\chi2 = 2.2197$, df = 1, p-value = 0.1363), or their interaction ($\chi2 = 0.1406$, df = 1, p-value = 0.7077) on the range shift. In contrast, species current suitable habitat and their migratory status could have both direct ($\chi2 = 7.275$, df = 1, p-value = 0.007; and $\chi2 = 4.1614$, df = 1, p-value = 0.04, respectively) and interactive effect ($\chi2 = 6.3078$, df = 1, p-value = 0.01) on species range shift. Post hoc analysis revealed that migratory species could experience a larger range shift compared to the non-migratory species (mean difference= 1.26, p= 0.04).

While comparing the range shift and elevation shift between the threatened and non-threatened species, I found that threatened species could experience higher range shift ($\chi2 = 10.947$, df = 1, p-value = 0.0009) and higher elevation shift ($\chi2 = 46.163$, df = 1, p-value = <<0.001) compared to the non-threatened ones.

Discussion

Climate change is considered one of the most critical threats to biodiversity, yet literature documenting climate change impact on tropical insects remains scarce (Taheri et al., 2021). Given that tropics contain enormous insect diversity, understanding climate vulnerability to tropical species is essential. Here, comparing the suitability distribution for 242 Bangladeshi butterfly species, I revealed that climate warming could severely impact many butterfly species. While the suitability might remain similar in some parts of the country (e.g., north-east), the future suitability could expand (e.g., towards north-east) and contract (e.g., from the central) in other parts. Although the direction of the shift in climatic suitability could be multi-dimensional, most species might shift towards the north. This finding is similar to VanDerWal et al. (2013), who analysed the distribution changes of 464 Australian bird species and found that both temperature and precipitation influence changes in species' distributions, such that the resulting patterns of range shift are complex. In addition, many Bangladeshi butterflies could shift towards the north-east and south-east direction, mostly mountainous and forested habitats, whereas the remaining parts of the country mainly consist of grasslands (Chowdhury et al., 2021b). This finding supports that i) there could be a decrease in grassland species and an increase in forest species (Kwon et al., 2021) and that ii) elevational shifts are more pronounced than poleward shifts for tropical butterflies (Colwell et al., 2008; Chen et al., 2009).

Due to climate warming, the suitable habitat could primarily shift for all the Bangladeshi butterfly species (except for *Spindasis elima*); however, there could be a striking difference between the threatened and non-threatened species. While the suitable habitat could increase for 58% of species and decrease for 42%, most of the threatened species could experience range contraction. The centroid shift for the threatened species (55km2) could be lower than the non-threatened species (77km2); therefore, threatened butterfly species could be more vulnerable to climate change if they cannot adapt to the changing environment. This finding is similar to Mattila et al. (2011), where authors analysed the distribution shift among the threatened and non-threatened Finnish butterflies. Although the range of Finnish butterflies shifted substantially, threatened species moved very little (Mattila et al., 2011). Although Finnish threatened butterflies did not show any consistent direction of the shift (Mattila et al., 2011), I obtained contrasting result that most threatened Bangladeshi butterflies could shift toward a south-south-west direction. Additionally, the mean elevation of Bangladeshi butterflies could increase by about 2.4 times in the future climatic condition, which could be more extreme for the threatened butterflies. To safeguard the existential status of Bangladeshi butterflies, especially threatened species, the conservation managers, planners, and policymakers should take this into account in their efforts.

Climate warming will lead many species to move towards higher elevations to track suitable climatic niches (Walther et al. 2002). Nevertheless, the ability to track climatic niche differ markedly depending on the migratory behaviour of the species (Warren et al., 2001; Hill et al., 2002). By analysing 46 British butterflies, Warren et al. (2001) showed that the distribution range expanded for half of the mobile and generalist butterfly species, whereas the other generalists and 89% of the habitat specialists declined in distribution size. In another study, Chowdhury et al. (2021a) showed that while expanding its geographic range, the migratory tawny coster butterfly maintains its native climatic niche. Here I found that the amount of suitable habitat for the migratory species could increase significantly and that migratory butterflies could experience a more pronounced shift in suitability in the future climatic conditions comparing to the non-migrants. This result supports the hypothesis that migratory species perform better in tracking climatic niches (Warren et al., 2001).

The existing biodiversity is facing an existential crisis due to several anthropogenic stressors; however, none is as pervasive as climate change (Halsch et al., 2021). The current climate change has already impacted 27 million km2 (18.3% of land), which took place in all biomes (Elsen et al., 2021). Climate change has negatively impacted the distribution of 47% of 873 terrestrial non-volant threatened mammal species and 23.4% of 1.272 threatened birds species (Pacifici et al., 2017). Here, I showed that the future climate could be unsuitable for 2-30% of Bangladeshi butterfly species depending on the climate change scenarios. If the climate changes at a similar rate – as it is now, many butterfly species will go extinct. Wallace's understanding of tropical climate as "genial" dismisses the view that tropical climates can be vulnerable to climate change (Colwell et al., 2008). While safeguarding tropical insects, several steps need to be taken urgently.

Our current understanding of how climate change impacts tropical insects is limited: Detailed studies are required to assess climate change vulnerability (Basset & Lamarre, 2019; Janzen & Hallwachs, 2019; Montgomery et al., 2020; Wilson and Fox, 2021) — identifying species-level details on how climate change impacts physiology, life history and evolutionary traits; diversity, abundance, and distribution. Understanding the key drivers of species sensitivity and how it varies among different groups (e.g., threatened and non-threatened; migratory and non-migratory) is essential, where natural history collections can provide important historical information on climate change impact (Scheper et al., 2014; Kharouba et al., 2019; but see Ries et al., 2019). Further, developing decisive conservation strategies for tropical insects are needed, where spatial conservation prioritisation approaches can be beneficial and identifying factors limiting species' capabilities to colonise areas beyond their historical limits is vital (Lewthwaite et al., 2018). Developing efficient conservation strategies requires long-term biodiversity data, yet such data is vastly unavailable from most tropics. To solve the biodiversity data gap, citizen science activities can be highly beneficial. A two-week citizen science project, for instance, could generate comparable spatial coverage for social wasp species as four decades of recording by expert amateurs (Sumner et al., 2019; Wilson and Fox, 2020). Assessing climate change's impact on Bangladeshi butterflies was only possible because of utilising the citizen science data, given a vast proportion of the collated species distribution records were from Facebook. Scientists can engage the wider community to document insect distribution data from the tropics; however, developing standardised monitoring protocol with detailed guidelines before organising such surveys.

The climatic niche evolution rate of species is slower compared to the climate change rate (Quintero & Wiens, 2013), and failure to track climatic conditions may lead to range contractions and/or local extinctions (Moritz & Agudo, 2013; Wiens, 2016; He et al., 2018). Besides, climate change is not just a future threat but impacts many species in the current time (McCarty et al., 2001). Using the niche-overlapping analysis, I showed that about 54% of the climatic niche of Bangladeshi butterflies could shift in the future. Immediately detecting climate change response is vital to improve (or initiate) management strategies, counter species loss, and mitigate biodiversity impacts. Here, specific management strategies should include prioritising species-specific requirements. For example, butterflies mostly are tied to specific habitat types, and therefore, to survive, they will require coordinated movement of climatic conditions habitat types (including vegetation structure) to track conditions spatially (Peterson et al., 2004). Further, the adverse effects of climate warming on pollinators can exacerbate by homogenous and fragmented landscapes, limiting range shift opportunities and reducing micro-climatic buffering (Vasiliev and Greenwood, 2021), which emphasises the importance of considering landscape connectivity and habitat heterogeneity in conservation planning (Vasiliev and Greenwood, 2021). Similarly, increasing the number of floral resources could attract diverse insect groups, creating connectivity between forest patches could support range expansion, and protected habitat over elevational and vegetational gradients could help range-restricted species.

Protected area (PA) coverage in the tropics is relatively low. For example, only 4.6% of terrestrial land in Bangladesh is now protected, and most are too small to support viable biota (Chowdhury et al., 2021f). Increasing PA coverage could insulate species from human-induced climate change and meet the Post 2020 biodiversity framework targets, aiming to achieve 30% PA coverage by 2030 (Convention on Biological Diversity, 2020). When proposing new PAs, scientists need to include connectivity planning emphasising climate change impact, ensuring landscape permeability, creating the network of habitats, future habitat conditions, and prioritising intact habitats. In tropical mega-populated countries like Bangladesh, many people live inside or surrounding PAs; therefore, scientists need to engage local people in conservation.

This is the first study highlighting how climate change could impact the suitability distribution of South Asian butterflies; however, these results need to be interpreted cautiously. For example, the spatial distribution data of Bangladeshi butterflies are highly biased and are mostly distributed in the major cities (Chowdhury et al., 2021b, f), which might impact findings. However, I followed two approaches to handle sampling bias: i) spatial thinning process, where I filtered single occurrence record from each raster pixel (Aiello-Lammens et al., 2015), and ii) used the 'checkerboard2' evaluation method, which handles overinflation of model performance, at least that portion resulting from biased sampling (Muscarella et al., 2014; Chowdhury et al., 2021e).

Conclusion

While human-induced climate change is impacting biodiversity globally in a dreadful way, literature documenting the impact on tropical species remains vastly scarce. Using the climatic niche model, I compared the suitability under different climatic conditions. I showed that the about 42% species could undergo range contraction in the future climatic condition. Depending on the climatic scenario (different Socio-Economic Pathways), the future suitability could be entirely unsuitable for 2-34% of butterfly species. Rapid detection of how climate change impacts tropical insects is vital, especially to initiate management strategies, counter species loss, mitigate impacts on biodiversity, arrest insect decline globally, and meet the Post 2020 Biodiversity Framework targets.

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Code availability

All the R scripts are available in the following public GitHub repository: https://github.com/ShawanChowdhury/bd_butterfly_clim_change.

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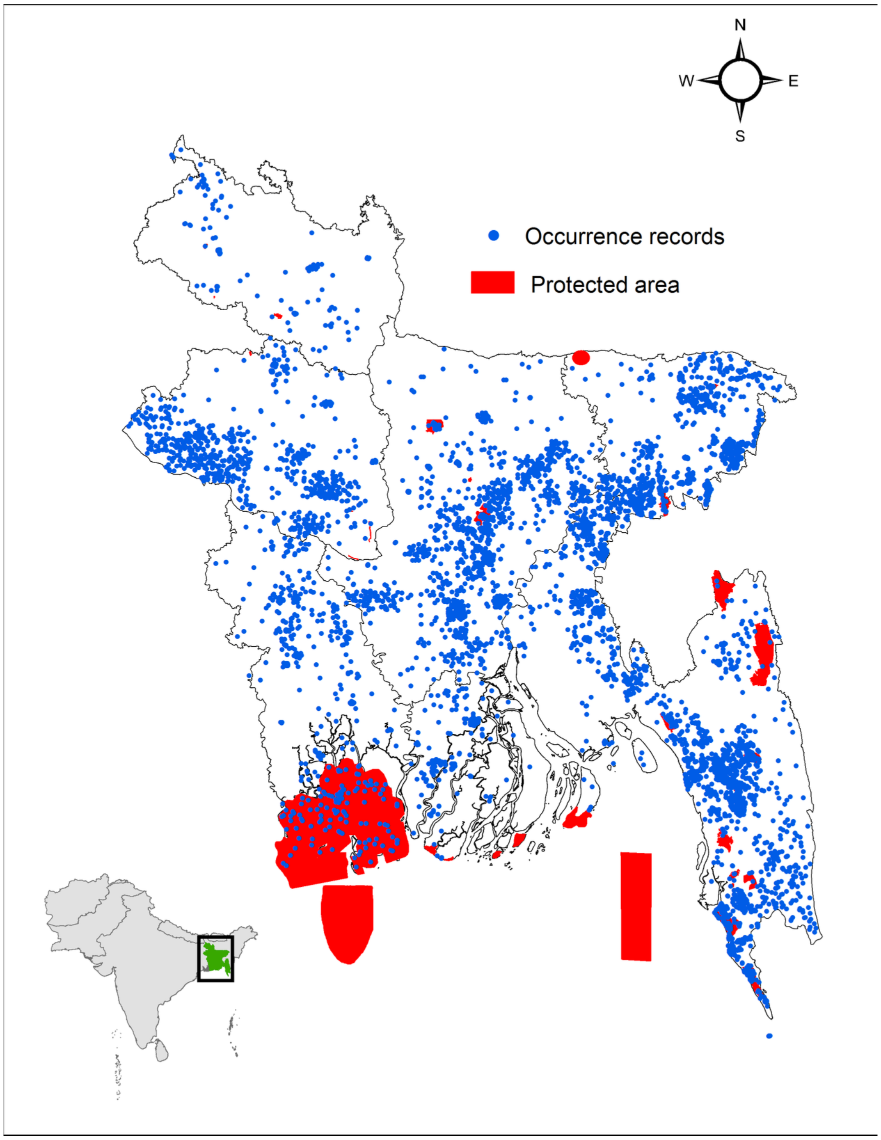
List of Figures

Figure 1. Map of Bangladesh showing the species occurrence records (blue) and the distribution of protected areas, where each 'blue' dot is representing one occurrence record. The inset map is showing the geographic location of Bangladesh in comparison to other South Asian countries. Some protected areas are difficult to spot because of their smaller size and too many distribution records around those areas.

Figure 2. Current (a) and future (b) potential suitability distribution, and the direction of shift in habitat suitability (c) of Bangladeshi butterflies. This figure is showing only the results of one future climatic scenario (ssp126, see the supplementary figure S3 and table S2 for the other climatic scenarios).

Figure 3. Changes in the suitability distribution of Bangladeshi butterflies. Here, these maps are showing regions where: the suitability remained same (a), expanded (b), and contracted (c). For each map, the colour bar is representing the number of species in each pixel. This figure is showing only the results of one future climatic scenario (ssp126, see the supplementary figures S4, S5, and S6 for the other climatic scenarios).

Figure 4. Changes in current and the future predicted suitability distribution of Bangladeshi butterflies. Here, a) is showing the centroid shift, b) is the range shift, and c) is the amount of niche overlap between the current and the future climatic suitability. This figure is showing only the results of one future climatic scenario (ssp126, see the supplementary table S2 for the other climatic scenarios).



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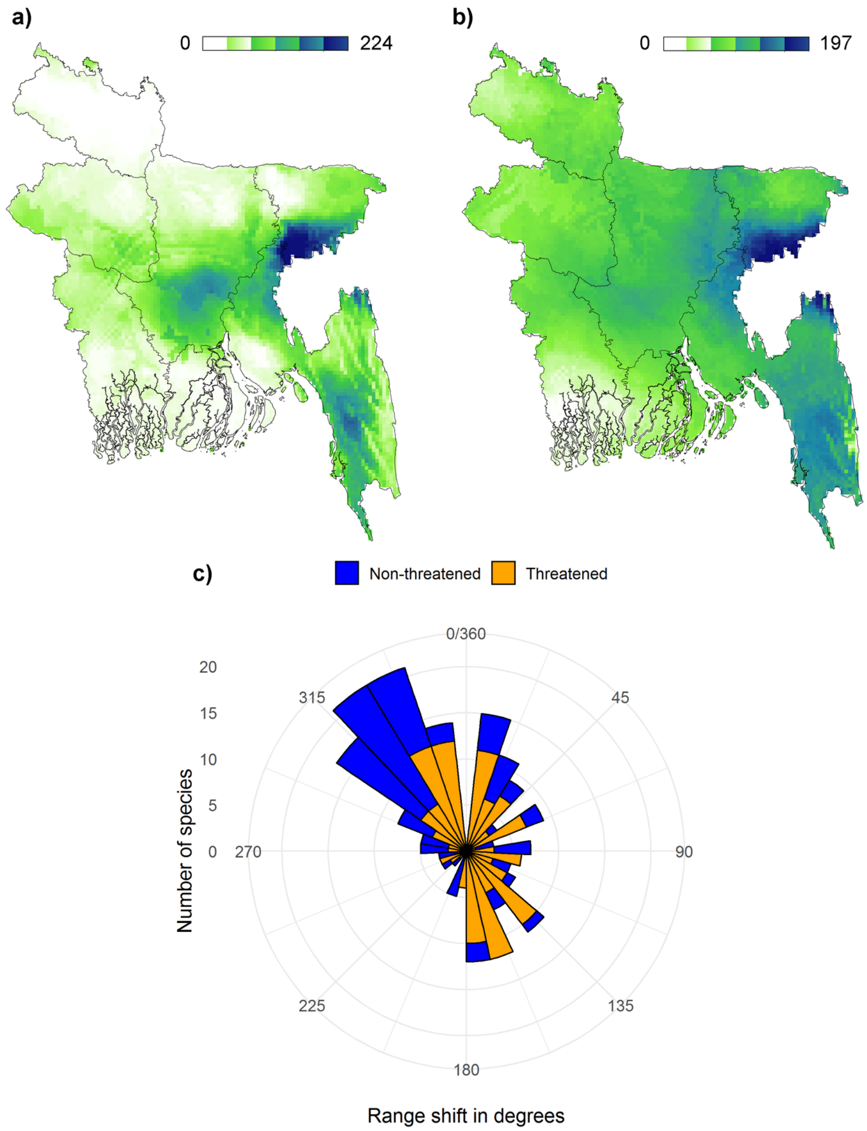

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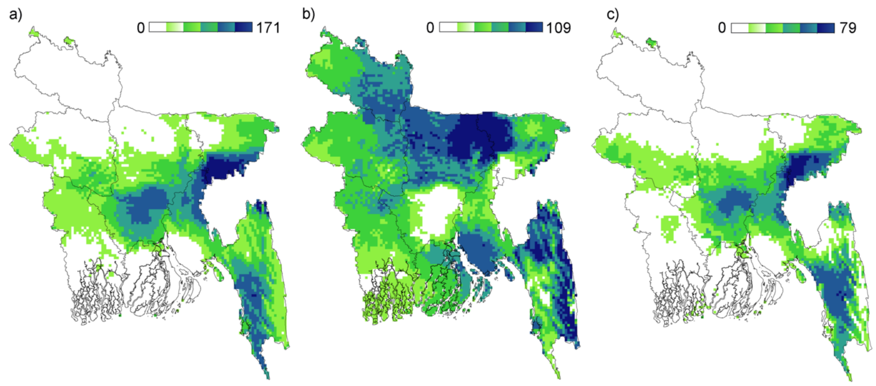

Figure 3. Changes in the suitability distribution of Bangladeshi butterflies. Here, these maps are showing regions where: the suitability remained same (a), expanded (b), and contracted (c). For each map, the colour bar is representing the number of species in each pixel. This figure is showing only the results of one future climatic scenario (ssp126, see the supplementary figures S4, S5, and S6 for the other climatic scenarios).

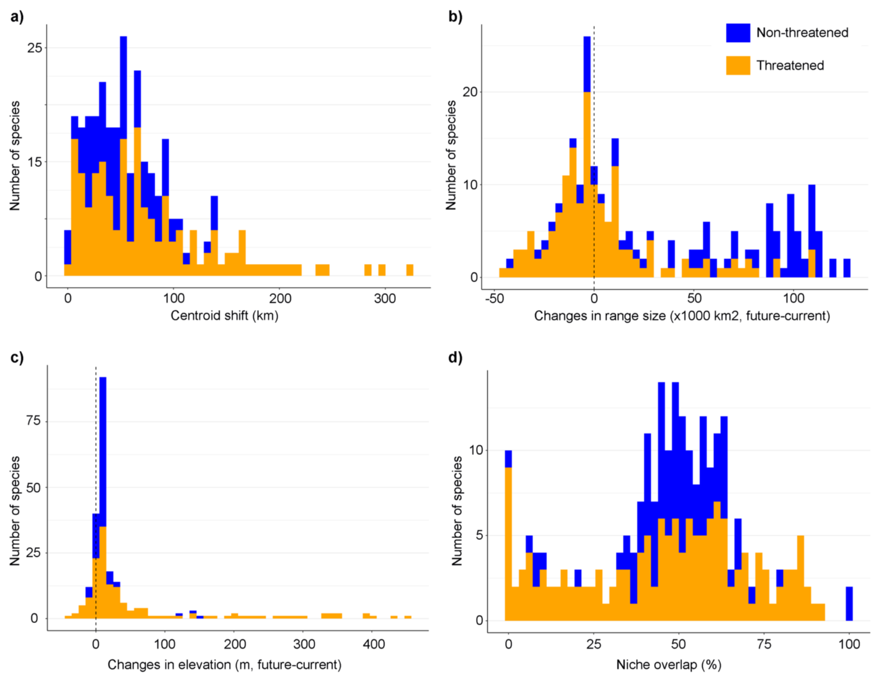

Figure 4. Changes in current and the future predicted suitability distribution of Bangladeshi butterflies. Here, a) is showing the centroid shift, b) is the range shift, and c) is the amount of niche overlap between the current and the future climatic suitability. This figure is showing only the results of one future climatic scenario (ssp126, see the supplementary table S2 for the other climatic scenarios).