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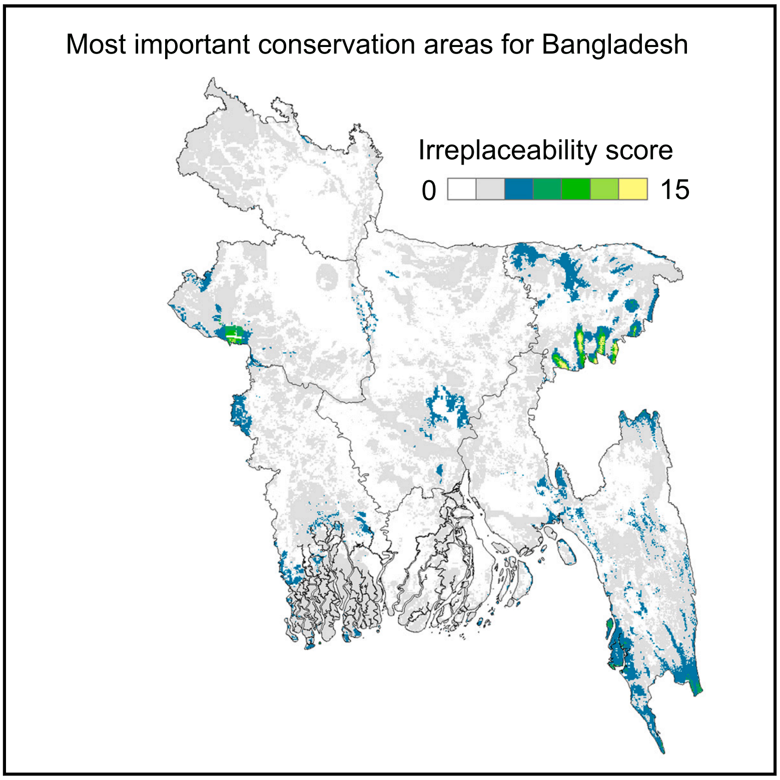
Insights from citizen science reveal priority areas for conserving biodiversity in Bangladesh

Graphical abstract



Highlights

- Social media data can improve our understanding of species distributions
- Only five of the 1,097 assessed species are adequately represented in Bangladesh
- The priority areas should cover 39% to ensure efficient conservation
- Most important conservation areas are distributed in the northeast and southeast regions

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In brief

Using species locality data from a range of sources, we reveal that only five species (0.004 of 1,097 species) are adequately represented by the current protected-area system of Bangladesh. We identify the most critical conservation areas to ensure efficient conservation.

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Insights from citizen science reveal priority areas for conserving biodiversity in Bangladesh

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SCIENCE FOR SOCIETY Most species are distributed in the tropics, yet our understanding of tropical biodiversity distribution remains under-represented. With the increasing popularity of social media, many people are posting species photographs, which can be used to reduce biodiversity data gaps. We combine species distribution data from Facebook and the Global Biodiversity Information Facility to assess the protected-area representation for Bangladeshi taxa and identify the most important conservation areas. Only five of the 1,097 assessed species are well represented by the current protected-area system of Bangladesh. The priority areas, spanning 39% of Bangladesh, are distributed mostly in the northeast and southeast regions. Our findings can help Bangladesh in meeting the Kunming-Montreal Global Biodiversity Framework targets. Additionally, the approach can be readily applicable to other countries, especially for countries lacking comprehensive biodiversity databases.

SUMMARY

The tropics contain a vast majority of species, yet our understanding of tropical biodiversity is limited. Here we combine species locality data from scientific databases and social media to examine the coverage of species by existing protected areas in Bangladesh and identify priority areas for future expansion. Although protected areas cover 4.6% of Bangladesh, only five species (0.004% of 1,097 species) are adequately represented, and 22 species are entirely absent from the existing protected-area system, including seven threatened species. Our spatial prioritization identified priority areas comprising 39% of Bangladesh, mainly in the northeast and southeast. The most irreplaceable areas (top 10%) are in hill forests and, to a lesser extent, agricultural landscapes. Our findings inform conservation policies for the Bangladesh government in order to meet the Kunming-Montreal Global Biodiversity Framework targets. In general, the approach can be broadly applicable to countries with limited data in global biodiversity repositories.

INTRODUCTION

Goal 3 of the Kunming-Montreal Global Biodiversity Framework (GBF) aims at achieving 30% protected-area coverage by 2030 (Convention on Biological Biodiversity[1]). Achieving such spatial targets requires having detailed species distribution records from which to identify priority conservation areas for establishment of protected areas.[1] Such detailed species distribution data are mostly unavailable, especially in the tropics.[2,3] While different citizen science applications (e.g., eBird, iNaturalist) are transforming biodiversity knowledge and reducing the distribution data gaps,[4] such applications are yet to become popular in highly biodiverse tropical countries, particularly in South and Southeast Asia.[5] In contrast, with the popularity of social media, digital photography, and mobile phones, millions of people nowadays post their biodiversity photographs on social media channels, which could be used in conservation assessments.[6,7] A recent study collated ~45,000 species occurrence records from just seven Facebook groups in Bangladesh and showed that most records were for threatened species that lacked records through systematic surveys.[5]

Bangladesh forms part of the Indo-Burma biodiversity hotspot and is home to many globally threatened and charismatic species, such as the tiger (*Panthera tigris*), hoolock gibbon (*Hoolock hoolock*), spoon-billed sandpiper (*Calidris pygmaea*) and the Ganges river dolphin (*Platanista gangetica*).[8–11] In addition to being globally important for biodiversity, Bangladesh is also the most densely populated developing country in the world (at least among countries with >10 million people), and millions of people are directly dependent on its natural resources.[12–15] This has resulted in rapid degradation of remaining natural environments with an increasing number of people living inside natural habitats and extracting resources.[15–20] Like many other Asian countries (e.g., 150,000 km^2 primary forests of southeastern Asia have been cleared), Bangladesh is also rapidly losing its pristine forests and other natural habitats.[15] Nearly 40% of land has been cleared in the last eight decades, and less than 11% of the natural forest remains; this has led many species to decline dramatically.[21–24]

Protected areas play a major role in conserving biodiversity worldwide.[25–27] In Bangladesh, they are especially important because they abate key anthropogenic stressors that impact native species, such as forest loss, conversion of natural forests to plantations, conservation-linked interventions such as mangrove plantations, and habitat fragmentation.[15,28–34] Only 4.61% of land (including inland waters) and 5.4% of marine areas in Bangladesh are currently protected.[35,36] Additionally, only 0.66% of terrestrial and 0.87% of all protected areas are under effective management, and no protected areas feature in the International Union for Conservation of Nature (IUCN) Green List of Protected and Conserved Areas,[36] the global standard for effective, equitable, and successful protected areas.[37] The existing protected-area system displays a significant imbalance in its distribution, as a considerable proportion of protected areas are situated in mangrove forests and marine habitats,[15] and in southern, southeastern, and southwestern Bangladesh, where prominent wildlife species such as tigers and Asian elephants (*Elephas maximus*) reside.[15] While protected areas are also discussed in a freshwater context, their effectiveness is much less clear,[38] especially since, in many cases, protected areas were not established with specific freshwater goals in mind. Nevertheless, two of Bangladesh's protected areas are designated as Ramsar sites (Wetlands of International Importance), the Sundarbans (transitional zone between freshwater and marine) and Tanguar Haor in the Surma River floodplain.[39] Overall, owing to the inadequate protected-area coverage, immense anthropogenic pressure on the existing biodiversity, the recently negotiated GBF, and the need for development, additional conservation efforts are now urgent.[15,40] Any biases in protected-area coverage may hinder the ability of the protected-area system to safeguard species. For instance, existing protected areas cover less than 2% of the geographic range of Bangladeshi butterflies.[14] Since one in four species is threatened in Bangladesh,[41] conservation efforts are urgently needed to prevent the extinction of the remaining species.

Here, we examine the coverage of the national protected-area system and identify priority areas to address conservation shortfalls. To achieve this, we collated species occurrence records of various taxa (amphibians, birds, butterflies, crustaceans, freshwater fishes, mammals, and reptiles) across the country from traditional and social media sources and fitted ecological niche models to generate species' habitat suitability maps. We then evaluated the extent of existing protected areas by overlaying the suitability maps with the boundaries of protected areas and comparing species' coverage to target thresholds. To address shortfalls in the current protected-area system, we identified priority areas for future protected-area establishment and conservation actions in Bangladesh. We reveal that only five of 1,097 species are adequately represented by the current protected-area system of Bangladesh and that 39% of areas should be protected to conserve all species efficiently. While this study is focused on Bangladesh, we demonstrate how conservation planning can be supported in data-deficient regions through the use of crowdsourced species data as the foundation for rigorous spatial planning.

RESULTS

Protected-area system assessment

Overall, we obtained data for 1,097 species, of which 288 species are nationally threatened (vulnerable, endangered, and critically endangered), 765 species are non-threatened (Least Concern and Near Threatened), and 44 species are Data Deficient (see Figures S1–S3,[41]). The mean protected-area coverage (percentage of range area that overlaps protected areas) of Bangladesh's IUCN-listed species was 6.3%; however, only 277 species (25%; data deficient, 11 species; non-threatened, 196 species; threatened, 70 species) exceeded this coverage. Protected-area coverage was >50% for 14 species (highest for the butterfly *Euploea crameri* with 95.2% coverage), >16% for 92 species, and <2% for 405 species (37% of 1,097 species; Figure 1). Overall, protected-area coverage was slightly higher for threatened species (7.4%) than non-threatened species (5.8%), whereas for the Data Deficient species, coverage was close to overall mean protected-area coverage (6.6%). Protected-area coverage varied substantially among major taxonomic groups, being highest for crustaceans (13%) and lowest for freshwater fishes (3.4%). For other major groups, protected-area coverage was as follows: mammals (9.6%), reptiles (9.5%), birds (6.9%), amphibians (5.5%), and butterflies (4.6%; Figure 1 and Table 1).

A total of 22 species were not covered by any protected areas, including 12 non-threatened, seven threatened, and three data-deficient species (see Table S3 for more details). These species were distributed in all the major taxonomic groups except for amphibians. Five of these species had very large range size (>9,000 km^2) (Indian cormorant, *Phalacrocorax fuscicollis*; Eurasian golden oriole, *Oriolus oriolus*; spotted bush warbler, *Bradypterus thoracicus*; common guava blue, *Virachola isocrates*; common silverline, *Spindasis vulcanus*), of which three were birds and two were butterflies (see Table S1 for more details).

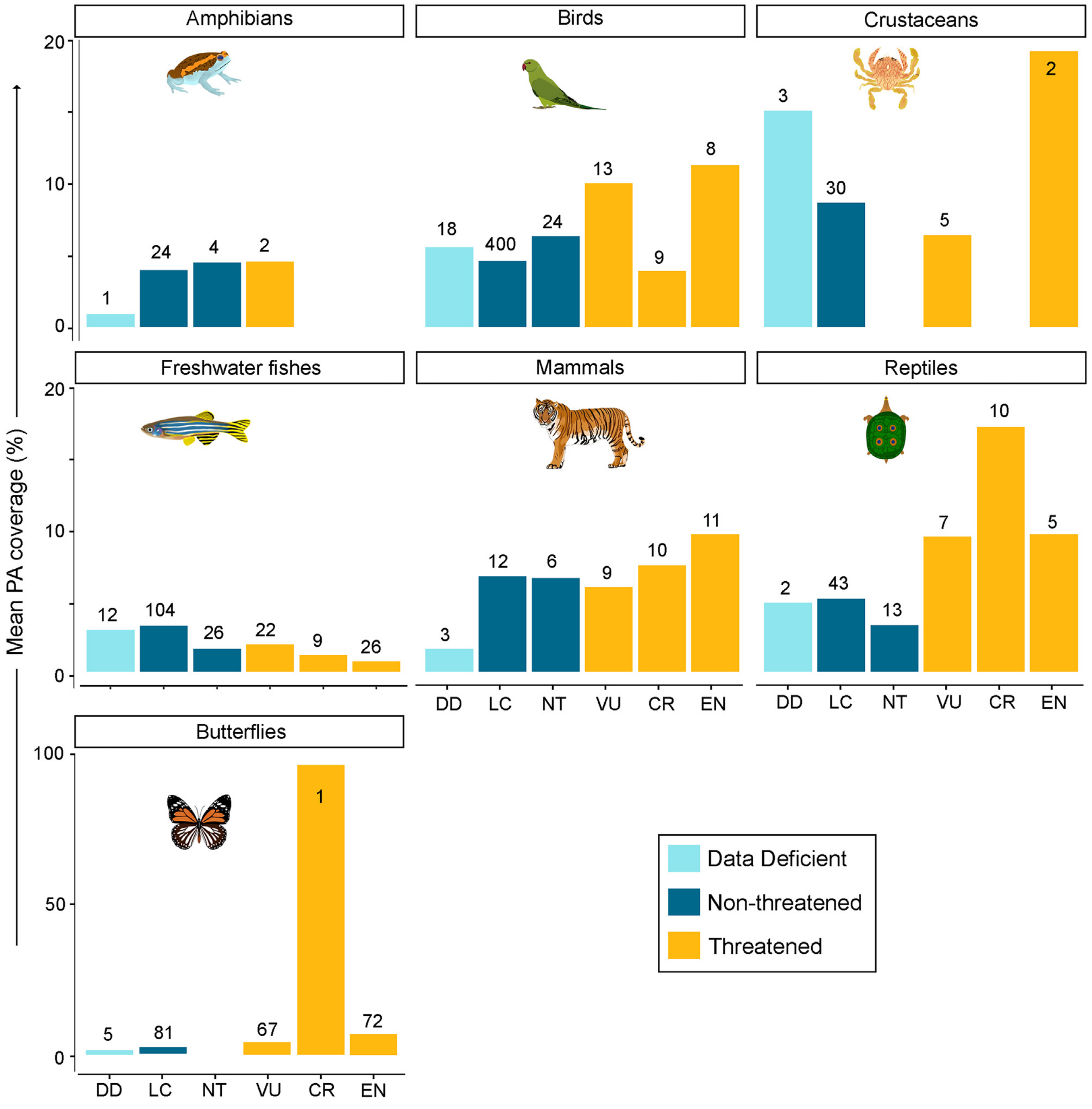

Figure 1. Mean percentages of protected-area coverage for Bangladesh IUCN-listed species by taxonomic group and IUCN Red List status
Labels denote the number of species associated with a given taxonomic group and IUCN Red List status. The IUCN Red List statuses include Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). To help facilitate interpretation, the statuses have been categorized into Data Deficient, non-threatened, and threatened status categories (shown in light blue, dark blue, and orange, respectively). The missing bar indicates the absence of that IUCN Red List category in that particular taxon.

We found that only five species met the protected-area representation target (i.e., northern river terrapin, *Batagur baska*; Asian small-clawed otter, *Aonyx cinerea*; buffy fish owl, *Ketupa ketupu*; masked finfoot, *Heliopais personata*, and spotted black crow butterfly, *Euploea crameri*). Four of these are threatened (two critically endangered, two endangered), and the other (*Ketupa ketupu*) is nationally data deficient. The area of suitable habitat for species meeting the target representation ranged between 1,310 and 3,717 km^2, and all these species had >76% protected-area coverage (see Table S1).

Spatial prioritization

Priority areas spanning 39% of the country (58,180.12 km^2) would need to be protected to ensure adequate representation of species (see the richness pattern in Figure S3). Although these priority areas are distributed throughout the country, there is a

Table 1. Mean protected-area coverage and target shortfall (decimals converted to the nearest integer) of the IUCN-listed species of Bangladesh by taxa (IUCN Bangladesh, 2015)

Taxa	Mean suitable habitat (km^2)	Mean protected-area coverage (%)	Mean protected-area coverage target (%)	Mean target shortfall (%)
Amphibians (31 species)	21,521	5.5	50	45
Birds (472 species)	14,257	6.9	56	49
Butterflies (226 species)	14,022	4.6	58	53
Crustaceans (40 species)	16,813	13	58	45
Freshwater fishes (197 species)	25,786	3.4	45	42
Mammals (51 species)	12,915	9.6	64	54
Reptiles (80 species)	15,991	9.5	61	51

substantial variation in their placement across different administrative divisions (Figure 2A). About 26% of these priority areas are located in Chattogram (southeast region of the country), and only 5% are located in Barishal (south-central region). When comparing with the area of the division, >50% of the available area is selected in Khulna (southwest), Chattogram, and Sylhet (northeast), whereas about 35% of the area is important in Dhaka (central part; Figure 2A). Although most priority areas have relatively low irreplaceability scores (30% were <0.001), the priority areas with the highest scores (top 10%) are found in the northeast (Sylhet) and the southwest (Chattogram) parts of the country (Figure 2B).

Priority areas are mostly distributed in places with a low level of anthropogenic impact (as measured by the 2018 version of the human footprint index[42]; see experimental procedures for details). For instance, 25% of priority areas were located in places that had a human footprint score <10, 64% in places with a score between 10 and 20, and only 3% of places were in places with a score >25 (Figure 2C). As the human footprint index ranges from 1 to 100,[42] our findings indicate that most species prefer low-human-intensity areas. Additionally, when considering current patterns of land use across Bangladesh[43] (see experimental procedures for details), approximately 60% of the priority areas were located in croplands, 30% in forests, and 7% in permanent water bodies (Figure 2D). Overall, these results suggest that there are many important places for biodiversity conservation in Bangladesh that are impacted by anthropogenic activities, so conservation efforts will need to navigate trade-offs between conservation objectives and other land-use demands.

DISCUSSION

Protected areas play a crucial part in biodiversity conservation by buffering biodiversity from human-induced threats.[30,44–47] However, the performance of protected areas in conserving species and their habitat is poorly known in many tropical countries.[15,48] Here, using Bangladesh as a case study, we showed that mean protected-area coverage was very low (6.27%) for species listed on the national Red List of the country, although coverage was slightly higher for threatened species (7.4%) than non-threatened species (5.8%). Only five species met the protected-area representation target, and the shortfall in protected-area coverage was higher among threatened species. This finding illustrates the low coverage by protected areas typical of many tropical countries and indicates that a large proportion of many species' distributions remains unprotected.[49–52]

Only 4.61% of the terrestrial area (including inland waters) is currently listed as protected areas in Bangladesh.[36] Moreover, current protected areas are highly biased toward the southwest, and most protected areas are very small: 38% (16 of 42) are <10 km^2, and even more extremely, three protected areas are less than 1 km^2.[15] The Kunming-Montreal GBF targets 30% protected-area coverage by 2030, to which Bangladesh is a signatory.[1] To meet this highly ambitious target within Bangladesh, the country needs a 5-fold increase in protected-area coverage. Our spatial prioritization shows that to ensure adequate representation across threatened species, Bangladesh's government needs to protect at least 39% of the land area, which is substantially higher than the GBF's targets. Most people in Bangladesh are largely dependent on agriculture, and >75% of Bangladesh is croplands, many of which are (or are surrounded by) critical conservation areas. The government needs to find a way to handle this issue: a good starting point would be to protect the boxed locations shown in Figure 2B. To mitigate biodiversity loss and better represent current biodiversity, these new protected areas could be established mostly in the northeast (Sylhet) and southeast (Chattogram) of the country (Figure 2). However, when creating new protected areas, decision-makers need to account for people, their livelihoods, and biodiversity, since empowering the environmental stewardship of indigenous peoples and local communities is critical to conserving biodiversity across the planet.[53–56] While establishing new protected areas is an option, other effective area-based conservation measures can be an effective solution too, particularly in production landscapes. It is challenging to expand the protected-area system in agricultural landscapes in Bangladesh, as food production is critical. Where agroforestry can be a solution, there is a need for sectoral coordination and true political commitment (which is common in most tropical developing countries). Further, it would also be worth examining how the protected-area requirements vary by taxonomic groups, for example, whether large mammals can act as a surrogate for other taxa (e.g., insects). Harnessing the data from Bangladesh's national Red Lists can also help to identify key biodiversity areas as a first step in delineating sites of importance for biodiversity.[57]

Bangladesh is exceptionally endowed with rich biodiversity and harbors many globally threatened species,[41,58–60] yet the spatial distribution of many species is poorly understood.[5,61]

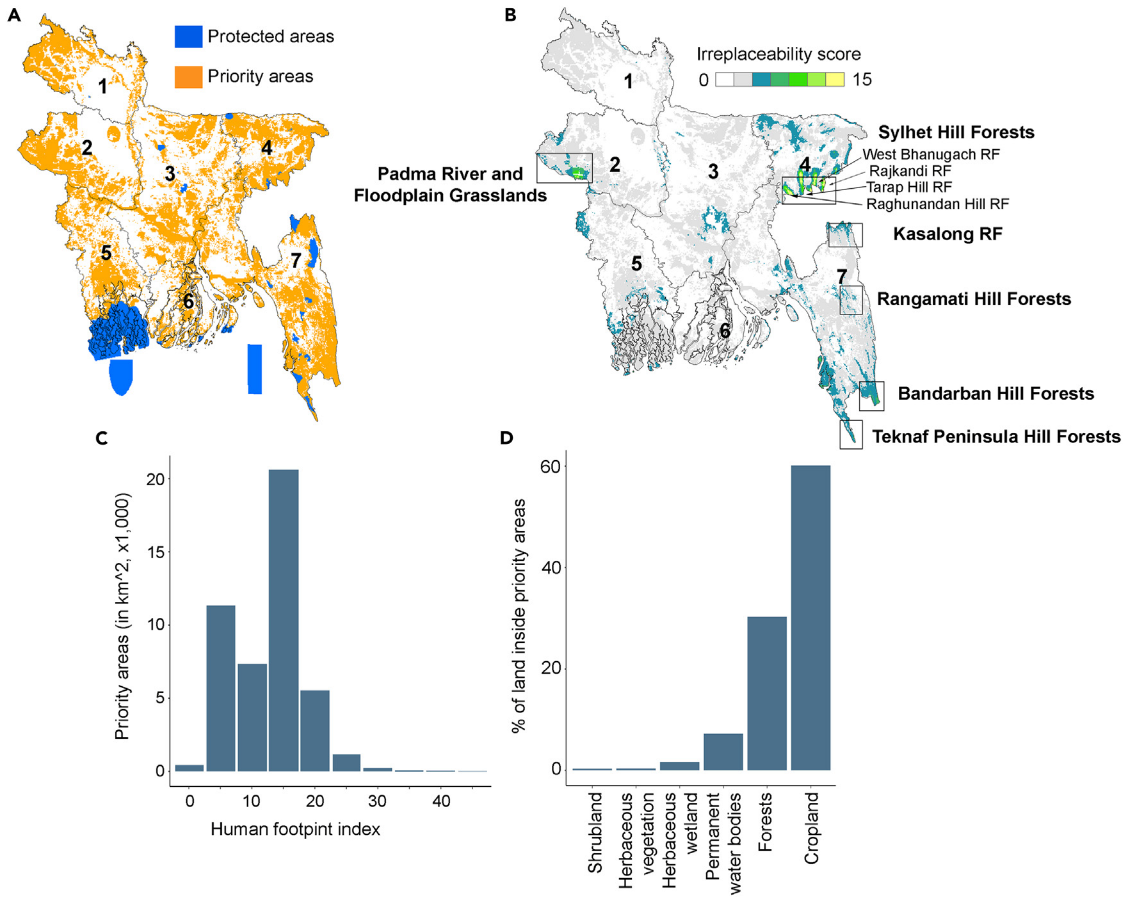

Figure 2. Most important conservation areas of Bangladesh

Maps show (A) current protected areas and priority areas for meeting species representation targets and (B) irreplaceability scores for both current protected areas and priority areas. In brief, irreplaceability scores were calculated following Ferrier et al.,[111] wherein scores were calculated separately for each species (with values ranging between 0 and 1) and then summed together to produce an overall irreplaceability score for each planning unit. Thus, irreplaceability scores with a value greater than 1 represent critical areas for conservation. Within these maps, labels demarcate administrative divisions of Bangladesh (1, Rangpur; 2, Rajshahi; 3, Dhaka; 4, Sylhet; 5, Khulna; 6, Barishal; and 7, Chattogram) and important ecosystems. Histograms show the distribution of (C) human footprint scores and (D) land use within priority areas.

Over 17% of the nationally assessed species are data deficient at the country scale.[41] This lack of spatial data is also prominent in global biodiversity repositories, with over 25% of our data sourced instead from social media and recent publications.[5,62] Besides data limitations, the available data are highly concentrated on certain taxonomic groups (e.g., birds) and on or around major cities (e.g., Dhaka).[24,61,62] About 55% of the spatial distribution records of our study are from Dhaka (central), whereas only 1.26% are from Rangpur (northwest). Researchers and conservationists should continue to encourage the broader public to use citizen science applications (e.g., eBird, iNaturalist)[5,63–67] to address data gaps in biodiversity data repositories. While niche models provide a good initial mechanism to model species distributions, such additional biodiversity data are needed to verify these estimated distributions and are also vital in confirming trigger species occurrence in potential key biodiversity areas.[57]

As is the case for many tropical countries, there are limited biodiversity data available from Bangladesh, especially in formal global repositories. However, with the ubiquitous popularity of digital cameras and smartphones and the availability of fast internet, thousands of people are sharing their biodiversity observations on Facebook.[5,68,69] Indeed, over one-quarter of our data are from Facebook,[62] including many records of threatened species. Data obtained from Facebook also cover a much wider distribution of species in comparison with the Global Biodiversity Information Facility (GBIF).[5] If we had only relied on global biodiversity repositories for this assessment, we would have missed distribution data on hundreds of threatened species. This illustrates the potential of additional biodiversity records from non-traditional sources when making local or international-scale conservation assessments.[5–7] Future research could usefully focus on developing a tool to extract biodiversity data from social media (e.g., Facebook, Twitter, Flickr) and deposit it into major global biodiversity repositories, such as GBIF.[5,68] We recommend that researchers compile biodiversity data from as many sources as possible and also assess how conservation decisions vary depending on whether records from non-traditional sources (e.g., Twitter, Flickr) are included.

Most threatened species in Bangladesh are forest species. Being a developing and densely populated country, natural resources are in high demand, impacting the forest reserves in both explicit and implicit ways.[14,15,70–73] In addition, with Bangladesh being among the top five inland fisheries globally,[74] aquatic resources play an important role in the nutrition, economy, employment, and culture of the country.[41] This puts substantial pressure on target species, which is compounded by other threats such as pollution, habitat loss, invasive species, and climate change,[41,75–77] and needs to be addressed in a spatial priority setting for conservation. For example, in our analysis, threatened fish are spatially under-represented in the protected area system (Figure 1). This could be because historically, protected areas were rarely designed according to the needs of aquatic species.[78,79] Studies elsewhere have also shown that the proportion of freshwater species with ranges substantially covered by protected areas is much smaller than for birds and mammals.[80] However, studies have also shown that by adequately integrating terrestrial and freshwater conservation planning, freshwater benefits were substantially increased with only a minor loss in benefits to terrestrial species.[79]

Several recently published studies from Bangladesh revealed the importance of "unconventional" areas such as urban green spaces in biodiversity conservation,[14,24,81–85] and our spatial prioritization approach identified many important areas around major cities. Chowdhury et al.[24] documented nearly 45% of the national butterfly species (137 of 305 species) in urban green spaces of Dhaka; 40% of these 137 species were nationally threatened, and specifically, one urban protected area (National Botanical Garden) performed relatively better than other green spaces in the analysis. Designating more protected areas and effective management in urban landscapes could attract many more species and reduce species vulnerability to anthropogenic disturbances,[86] and perhaps such sites could constitute valuable OECMs. Besides, the current protected areas do not yet represent the country's diverse ecoregions; for example, only four broad forest types are designated as protected areas.[87] Priority areas identified here could help inform conservation decisions made by the Bangladesh government.

Conclusions

We assessed how protected areas in Bangladesh cover the geographic ranges of a broad range of species. We showed that mean protected-area coverage is very low, and currently, only five species are adequately protected. However, our findings should be interpreted cautiously. For example, we did not measure the effectiveness of individual protected areas, calculate the rate of habitat loss and natural resource harvests inside their boundaries, nor measure whether local habitats inside protected areas are (or will remain) suitable in an era of rapid environmental change. Specifically for freshwater species, the effectiveness of protected areas is often questioned, since freshwater needs—given their connectivity and close links with the landscape they drain—are rarely taken into account when designing and delineating terrestrial protected areas.[38] Future studies could assess how anthropogenic climate change will impact biodiversity in tropical countries, such as Bangladesh, and find an efficient way to tackle the situation. We hope our study will create a baseline that the policymakers of Bangladesh could use to meet the Kunming-Montreal GBF targets.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Shawan Chowdhury; dr.shawanchowdhury@gmail.com.

Materials availability

This study did not generate new unique materials.

Data and code availability

Both the GBIF[88] and Facebook[62] data are publicly available.

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

Study system

We obtained the most recent published checklists of wildlife (amphibians, birds, butterflies, crustaceans, freshwater fishes, mammals, and reptiles) in Bangladesh from the Red List of Threatened Species by the IUCN Bangladesh.[41] Although we originally considered all 1,619 species that have been assessed at the national level,[41] we only obtained adequate spatial data for 1,097 species to allow for habitat suitability modeling. We also gathered national and global threat status data for these species from the IUCN Red List.[41] We collected climatic data from the WorldClim database (https://worldclim.org/) and land-use data from Copernicus Global Land Service.[43] We performed all the analyses using the R statistical computing environment (version 3.5.3).[89]

Before fitting any environmental niche models, we checked collinearity among the WorldClim variables and removed highly correlated ($r > 0.75$) variables.[90] We removed 11 climatic variables (bio2, bio4, bio5, bio6, bio7, bio8, bio10, bio12, bio13, bio16, and bio19) and retained eight climatic variables for the model fitting.

Species occurrence records

We collated species occurrence records to fit environmental niche models. To achieve this, first, we obtained records from the GBIF (https://www.gbif.org/)[88] using the "rgbif" package (version 3.7.2).[91] Since this procedure did not yield an adequate number of records for modeling—with only a median of 11 records per species—we further enriched our datasets by obtaining additional records from social media posts that contained species name, location, and date. Following Chowdhury et al.,[5,14,92,112] we searched for records posted in seven Facebook groups: Birds Bangladesh (https://www.facebook.com/groups/2403154788); Deep Ecology and Snake Rescue Foundation (https://www.facebook.com/groups/959896627527624); Biodiversity of Bangladesh (https://www.facebook.com/groups/249240636186853); Butterfly Bangladesh (https://www.facebook.com/groups/488719627817749); Mammals of Bangladesh (https://www.facebook.com/groups/647662968655338); Amphibians and Reptiles of Bangladesh (https://www.facebook.com/groups/560709511527645); and Biodiversity of Greater Kushtia (https://www.facebook.com/groups/244807066739477). Within each of these groups, we searched for each species (separately) by their common name (as used by IUCN Bangladesh[41]), double-checked the identification in each photograph, and georeferenced (latitude and longitude) the locations of the observations using Google Maps (https://maps.google.com/). In this way, we evaluated all the posted photographs in that Facebook group. We excluded photographs if the identification was incomplete (not up to species level) or incorrect, the photograph was not clear (from the taxonomic viewpoint), or if the location information was unspecified.[5,14,92] For a detailed data extraction method from Facebook, please check Chowdhury et al.[112] Finally, we scanned published resources (referenced publications from IUCN Bangladesh[41]) for additional occurrence records.

Data cleaning

We cleaned the species' occurrence records to prevent erroneous records from negatively impacting environmental niche models. To achieve this, we removed duplicate records, records with precision uncertainty over 10 km, imprecise coordinates (zero coordinates, integers, records in oceans), and coordinates associated with incorrect locality information.[5,14,92] These procedures were completed using the CoordinateCleaner R package (version 2.0.20).[93] We also applied a spatial thinning routine to ameliorate the negative impacts of sampling bias using the spThin R package (version 0.2.0).[94] These thinning routines were applied using an 833 m distance threshold to keep a single occurrence record at 0.693 km^2 area. After applying all these data-cleaning procedures, the resulting dataset contained 57,147 records of 1,153 species (Figure S1).

Habitat suitability maps

We fitted MaxEnt models to generate habitat suitability maps using the ENMEval R package (version 0.3.1).[95] These models are well suited for our analysis because our occurrence records are presence-only data.[96–100] For each species, we fitted models using nine predictor variables (eight climatic variables and one land-use variable) with 10-fold cross-validation and 5,000 randomly generated background records at 0.693 km^2 resolution. To help reduce the negative impacts of sampling bias and spatial auto-correlation on model performance, the folds were generated by overlaying the presence and background records with a spatial grid, assigning the records to particular grid cells, and then randomly assigning grid cells to particular folds.[95] To further improve model performance, we performed a calibration procedure that involved fitting them under different combinations of parameters. Specifically, this procedure involved fitting the models under six feature class combinations ("L," "LQ," "H," "LQH," "LQHP," and "LQHPT") and eight different regularization multipliers (i.e., ranging from 0.5 to 4, in increments of 0.5). The models were evaluated using the area under the curve (AUC) statistic. After identifying the best model for each species, we used them to generate continuous habitat suitability maps across the study area. We then applied thresholds to convert the continuous maps into binary maps, resulting in maps that denote the presence or absence of suitable habitat conditions. The threshold values were specified by maximizing the sum of the sensitivity and specificity statistics.[101] Since the best models all had an AUC statistic greater than 0.7 (mean AUC = 0.92), we are confident that they are suitable to address the aims of our study.

The binary habitat suitability maps were used for subsequent analysis. We had 1,097 species for the final analysis. We extracted built-up areas from the land-use map and removed suitable habitats that fell within these areas for each species.

Protected-area data

We obtained boundaries for protected areas in Bangladesh using the wdpar R package (version 1.3.3).[102] After obtaining the most recent version of the World Database on Protected Areas, we cleaned the data following standard practices.[14,103,104] In brief, these practices included reprojecting the data into an equal-area coordinate system (World Behrmann; ESRI: 54017); excluding UNESCO biosphere reserves (due to high anthropogenic impacts)[105] and sites with unknown or proposed status; and buffering protected areas denoted as point localities and buffering them to their reported extent. These procedures resulted in boundaries for 42 protected areas. Finally, we rasterized the protected-area boundaries at 693 m^2 (833 m × 833 m) resolution using the *fasterize* R package (version 1.0.3).[106] We obtained 42 protected areas for the analysis.

Protected-area system assessment

We evaluated the species coverage of existing protected areas within Bangladesh. To achieve this, we overlaid the species' binary habitat suitability maps with the protected-area data to measure the percentage of each species' distribution covered by existing protected areas. We then compared their level of coverage to a target threshold (termed "representation target").[14] These targets were set following a modified version of standard practices for global analysis.[104,107] We set the target at 100% for species with a distribution of equal to or less than 1,000 km^2 and 10% for those with 148,460 km^2 (area of Bangladesh), and interpolated on a log-linear scale between these thresholds using the *prioritizr* R package (version 7.1.1).[108]

Spatial prioritization

We identified priority areas to address target shortfalls in the existing protected-area system. To accomplish this, we generated a single prioritization based on the minimum set formulation of the reserve selection problem. Specifically, the grid cells (mentioned earlier) were used as planning units for the analysis, the species' binary habitat suitability maps were used as features for the analysis, and the representation targets (as described for the gap analysis) were also used for the analysis. As such, the prioritization was constrained to meet the representation targets for each and every species assessed in the gap analysis. To account for opportunity costs associated with implementing conservation areas, it was also generated using the human footprint index[42] as cost data.[104] Additionally, to ensure that priority areas complement existing protected areas, existing protected areas were locked in. These analyses were completed with an optimality gap of 10% via the *prioritizr* R package[108] and Gurobi optimization suite (version 8.1.0; Gurobi Optimization).[109,110] After generating the prioritization, we overlaid it with land-use data to facilitate interpretation.

To identify the most important priority areas in the prioritization, we ran the irreplaceability analysis for each planning unit selected in a solution using the *prioritizr* R package.[108] Here, to quantify the importance of planning units, we used Ferrier scores,[111] which measure importance based on how critical planning units are in meeting conservation targets.[108,111] Although some methods for calculating irreplaceability scores do indeed range between 0 and 1 (e.g., rescaled selection frequency values from the Marxan software), this particular score does not. Specifically, it is computed by calculating individual irreplaceability scores for each species for each planning unit (that range between 0 and 1) and then summing these values together to obtain an overall irreplaceability score for each planning unit. As such, the overall irreplaceability value can range between zero and the number of species, and planning units with an irreplaceability value greater than 1 are likely critical for the protection of one or more species.[108,111]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.08.025.

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AUTHOR CONTRIBUTIONS

S.C. conceptualized the idea. S.C., J.O.H., and R.A.F. developed the experimental procedures, and all authors contributed to the experimental procedures. S.C. conducted the analysis, and all authors contributed to the analysis. S.C. wrote the paper, and all authors contributed to the writing of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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