Title: On the Edge: Identifying priority areas for conservation of Fishing Cat, a threatened wetland felid, amidst rapidly altering freshwater landscapes

Authors: Tiasa Adhya^{1,3*}, Priyamvada Bagaria^{2,3}, Partha Dey³, Vanessa Herranz Muñoz^{3,4}, Anya Avanthi Weerawardana Ratnayaka^{3,5}, Ashan Thudugala^{3,6}, Aravind N.A.^{7,8}, James G. Sanderson³

Affiliations:

1 Centre for Conservation of Natural Resources, The University of Trans-disciplinary Health Sciences and Technology, Bengaluru, India

2 Indian Council for Forestry Research and Education, Dehradun, India

3 Fishing Cat Conservation Alliance, Texas, USA

4 School of Bioresources & Technology, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

5 School of Agriculture and Food Sciences, The University of Queensland, Australia

6 Center for Integrative Conservation, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Yunnan, China

7 SMS Foundation Center for Biodiversity and Conservation, Ashoka Trust for Research in Ecology and the Environment (ATREE), Bengaluru, India

8 Yenepoya Research Centre, Yenepoya (Deemed to be University), Mangalore, India

***Corresponding author:**

Tiasa Adhya

Email: adhyatiasa@yahoo.com

Abstract

1. Freshwater ecosystems have been most severely impacted in the Anthropocene with 27% of its species threatened with extinction. Fishing Cat is a globally threatened South and South-east Asian wetland felid that is also a highly rated Evolutionarily Distinct and Globally Endangered (EDGE) species, i.e., it is a global priority for conservation and research. Being an understudied species, knowledge gaps exist on its basic ecology, such as distribution and niche.
2. To address this, ensemble species distribution modeling (ESDM) was used to clarify doubts on its potential distribution and niche. To provide a relatable current context, loss of suitable habitat to urbanization (2010-2020) was estimated by analyzing range-wide survey data with environmental and anthropogenic variables (night-time lights and land surface temperature as proxies for urbanization).
3. Wetlands (18.36%) and elevation (17.15%) are the most important variables determining the ecological niche of Fishing Cat. It was predicted to be mainly restricted to low-elevation (<111 m) wetlands in river basins of South and South-east Asia. An estimated 23.74% suitable habitat was lost to urbanization.
4. Incrementally building on the ESDM outputs, high priority movement corridors and landscape conservation units were identified.
5. South Asia holds the core of the global Fishing Cat population with two very important regions - Ganges Brahmaputra Basin and Indus Basin - sharing transboundary areas with highly suitable habitat and many priority conservation units. The former is strategic to maintaining connectivity between South and South-east Asian Fishing Cat populations while isolation effects in the latter need investigation. Coastal wetlands of South-east Asia, though severely impacted, are crucial for the felid's persistence.
6. More than 90% of Fishing Cat's potential range lies outside the protected area network. Here, the felid can be adopted as a flagship species to conserve rapidly degrading low-elevation wetlands within a socio-ecological framework by involving multiple stakeholders.

Keywords: Ensemble Species Distribution Modeling (ESDM), Fishing Cat, freshwater, wetlands, landscape conservation prioritization, urbanization

1. Introduction

The alarming rates of species loss during the ongoing sixth mass extinction surpass pre-human background estimates and continue because of increasing anthropogenic threats (Barnosky et al., 2011; Tittensor et al., 2014; Burivalova, Butler & Wilcove, 2018). Freshwater ecosystems, which are lifelines to both society and diverse species assemblages, have been the most severely impacted by these unprecedented threats but remain under-prioritized in the conservation domain (Albert et al., 2020; Tickner et al., 2020). Occupying less than 1% of the Earth's surface, these ecosystems provide habitat to one-third of the world's vertebrate species and 10% of all species (Dudgeon 2019), yet freshwater biodiversity populations have experienced dramatic declines with wetlands being lost three times faster than forests (Gardner and Finlayson, 2018). Approximately 27% of freshwater species and 42% of the 70 wetland dependent mammals are threatened with extinction (Balian et al., 2008; Tickner et al., 2020). Increasing socio-economic development in productive lowland regions is a significant threat to freshwater ecosystems (Darwall and Freyhof, 2016). In clarion calls published recently, scientists have stressed on integrating modern technology with field based knowledge for tracking endangered species of high conservation value to develop global freshwater conservation strategies (Arthington, 2021).

Fishing Cat (*Prionailurus viverrinus*) is a member of the threatened freshwater mammalian guild (Veron et al., 2008). Moreover, it is a highly rated 'Evolutionarily Distinct and Globally Endangered' (EDGE) species (EDGE score > 4), i.e, a global priority for research and conservation, but remains understudied (Tensen, 2018). It is one among the only two felids to have morphological adaptations for a semi-aquatic hunting niche (MacDonald and Loveridge, 2010), despite modern felids being morphologically and ecologically similar due to their recent and rapid divergence (Johnson et al. 2006). These include a double-coated, water-resistant fur, partially webbed feet, a short and stubby tail that provides balance while hunting or navigating in water and half-sheathed claws that provide traction in mud and facilitates gripping of slippery prey like fish (Kitchener, 1991; Sunquist and Sunquist, 2014; Hunter, 2019). Further, fish is known to be an important prey species and the primary constituent of its eclectic dietary niche (Haque and Vijayan, 1993; Cutter, 2015; Mukherjee et al., 2016). Both its morphological adaptations and prey association therefore suggests a strong selection for thriving in wetland environments.

Confirmed records of its presence exist from Pakistan, India, Nepal, Bangladesh, Sri Lanka, Myanmar, Thailand, Cambodia, Vietnam and Java (Willcox, 2015; Mukherjee et al., 2016, Lin and Platt, 2019) while its presence in peninsular Malaysia, Sumatra, Lao PDR, Taiwan and China remains speculative at best (Duckworth et al., 2009; Sanderson, 2009; Jutzeler, 2010; Duckworth et al., 2010). Further, there is lack of clarity on its distribution even within range countries. For instance, was/is it present in India's western coast? Though there is anecdotal evidence and speculation of its occurrence there (Jerdon, 1874; Nowell and Jackson, 1996; Sunquist and Sunquist, 2014), recent surveys have failed to detect it (Janardhanan et al., 2014). Its actual distribution in South-east Asia still needs clarity with targeted research being conducted only in

Thailand and Cambodia (Cutter, 2015; Thaung et al., 2018; Chutipong et al., 2019). Moreover, recent records of its occurrence from relatively non-moist drier areas (Sadhu and Reddy, 2013; Talegaonkar et al., 2018) and higher altitudes (>1800 m) (Thudugala, 2015) further create confusion regarding limitations of the species' fundamental niche.

The tools and techniques offered by Geographical Information Systems (GIS) have immense potential in combining large scale ground information with remotely sensed satellite data and modeled spatial data layers to demarcate species' geographical ranges, identify its movement corridors (Jalkanen et al., 2020; Xiao et al., 2020), and pinch points of connectivity (Yu et al., 2021), leading to prioritization of regions for their conservation (Lin et al., 2020; Shrestha et al., 2021). Species distribution modeling (SDM) approach has demonstrated the applicability of machine learning in defining species-environment relationship and the geographic extent of species distribution (Ahmed et al., 2021; De Simone et al., 2021; Lozano, 2021). SDMs combine the theory of ecological niche (Hutchinson, 1957), with machine learning algorithms to estimate a set of conditions appropriate for the species, and thereby estimate its potential spatial extent of distribution. These predictive models combine species presence locations with environmental variables (Araujo and Guisan, 2006; De Simone et al., 2021) to not only estimate species' geographic extent but also identify the limiting environmental factors. However, performance of these predictive models may vary from case to case (Hao et al., 2019). Instead of selecting an individual algorithm, an ensemble of models harnesses better predictive power (Araujo and New, 2007; Hao et al., 2019; Lozano, 2021).

In the present study, we employed ensemble species distribution modeling (ESDM) to a) estimate the potential global distribution of Fishing Cat and b) identify factors limiting its fundamental niche. To understand the current extent of its distribution under the impact of urbanization, the most prominent marker of socio-economic development, we further c) estimated loss of suitable habitat to urbanization from 2010 to 2020. Incrementally building on the ESDM outputs, we identified d) critical movement routes in urbanized landscapes and e) Landscape Conservation Units (LCUs) to suggest conservation priority regions for maintaining global Fishing Cat habitat populations and connectivity.

2. Methods

2.1 Species Occurrences

Fishing Cat occurrences collected through field surveys by teams in respective Fishing Cat presence countries were collated (Appendix Data Sources). Only occurrences recorded through camera traps, or photographic evidence were used, while evidences that were not collected through systematic surveys (road kills, captures, dead specimens, museum specimens) were eliminated. Spatial filtering of the occurrence points was performed using a buffer of 4.6 km, assuming 20

km² (~4.6 km square grid) as the maximum home range for Fishing Cat (Sunquist and Sunquist 2014). The occurrences dataset was divided into temporal categories of those collected between 2010-2014 (T₁) and 2015-2020 (T₂). Here onwards we refer to the two time frames as T₁ and T₂. Records indicating road kill and conflict or negative interaction with humans were also retained for manual evaluation of model output.

2.2 Habitat Variables

Distribution models for Fishing Cat were developed accounting for two scenarios, an ecological scenario and an urban impact scenario. A set of 37 variables for the ecological scenario and two additional variables for the urban impact scenario were used (Appendix Data Sources). Values of the habitat variables were attached to the species occurrence locations using QGIS 3.10. Collinearity among the variables was computed using the R package ‘caret’ (Kuhn, 2008). Variables left after removing collinear variables (Fig 1 and 2), were also tested for Variance Inflation Factor (VIFs, Marquardt, 1970). The variables retained were – annual mean temperature (bio_1), mean temperature of warmest quarter (bio_10), precipitation of driest month (bio_14), precipitation of warmest quarter (bio_18), mean monthly Normalised Difference Vegetation Index (NDVI) for February (NDVI_Feb), mean monthly NDVI for September (NDVI_Sept), elevation, ecoregions and wetlands (CIFOR). For the urban impact scenario, night-time lights and land surface temperature (LST) (Ariken et al., 2020) were used in addition to the ecological variables. To compare between the ecological and urban impact scenarios, we retained all the variables from the former in the latter scenario. The bioclimatic variables, elevation, eco-regions and wetlands remained constant across the two time intervals. NDVI, LST and night-time lights were used for the years 2012-13 and 2019 in order to represent the respective time intervals T₁ and T₂. Since the maximum home range for the Fishing Cat (20 km²) was considered, bioclimatic layers of spatial resolution 2.5 minutes (~4.6 km) were selected and the other raster layers were resampled to 2.5 minutes spatial resolution. Considering the geographic scale of this study, all analyses were performed using Asia Lambert Conformal Conic meter projection.

2.3 Modeling Procedure

The ecological and urban impact scenarios were modeled for both T₁ and T₂. Hence, four different distribution models were developed representing the ecological scenario for T₁ (EcoT₁), ecological scenario for T₂ (EcoT₂); the urban scenario for T₁ (UrbT₁), and the urban scenario for T₂ (UrbT₂).

We used the ensemble modeling approach for developing the ensemble species distribution model (ESDM) for FC, using R package ‘SSDM’ (Schmitt et al., 2017). ‘SSDM’ is a robust and user-friendly platform for modeling ecological niche of the species, using mathematical representation of the known occurrences of the species (Guissan and Thuiller, 2005; Schmitt et al., 2017). The ensemble modeling approach has been proven to be useful in eliminating bias arising from single models and predicting more precisely (Araujo and New, 2007; Hao et al., 2019).

The model was supplied with a presence only occurrence records and calibrated to pick pseudo-absence/background points using the default strategy (Barbet-Massin et al., 2012) incorporated within the ‘SSDM’ package. Each algorithm was set for 15 replicate repetitions and ‘leave-out-one’ cross-validation strategy was used for evaluation of the ESDM. Receiver’s Operating Curve (ROC) was used for model evaluation and binary map threshold computation. Algorithm selection in ‘SSDM’ is automated. The algorithms which have an evaluation above a specified threshold, are only used in the final ensemble projection. A threshold ROC of 0.75 was set for algorithm selection. The algorithms which passed this filter were Random forest (RF), Support vector machine (SVM), Multivariate adaptive regression splines (MARS) and Classification tree analysis (CTA). Based on the model evaluation scores (Table 1), we retained RF and SVM for the final model predictions. The metric used for computing the threshold for binary maps was sensitivity-specificity equality (Liu et al., 2005; Jiménez-Valverde and Lobo, 2007). Scenario EcoT₂ was first parameterised using this procedure. Thereafter, EcoT₁, UrbT₁ and UrbT₂ scenarios were computed, keeping the model parameters constant, for comparability and uniformity among model outcomes.

Variable importance scores computation is automated in the ‘SSDM’ package. However, for variable response curves, random points were generated over the geographic range and values of all the variables used in the models and the probability surfaces were extracted to the points. The variable values were plotted against the probability scores using R package ‘ggplot2’ (Wickham, 2011). The limiting range of important variables determining Fishing Cat was estimated based on the occurrence data as was adopted by Mukherjee et al., 2010.

2.4 Loss of suitable habitat due to urbanization

The binary maps for the two scenarios and respective time intervals were used for calculation of suitable ecological niche for FC in the respective scenarios and the difference in the maps was calculated using the MOLUSCE 3.0.13 plugin in QGIS v2.18.2.

2.5 Habitat Connectivity

The ESDM based probability raster for UrbT₂ was inverted to produce a friction layer for the movement of FC across its habitats. The ‘Least Cost Corridors and Paths’ module in the SDM toolbox (Brown, 2014; Brown et al., 2017) was used for identifying the corridors based on the least cost paths (LCPs) on a friction/cost layer. Due to processing limitations at the spatial resolution of 2.5 minutes (~ 4.6 km), the friction layer for the LCP analysis using SDM toolbox was resampled to a resolution of 5 minutes (~ 9.2 km). We used the ‘percentage of LCP value’ method for selecting the least cost corridors (LCCs) as this method selects corridors based on site-specific LCPs (Chan et al., 2011; Brown et al., 2017). Fishing Cat occurrences for T₂ were used as input points. Due to the absence of any physical connection between Sri Lanka and the rest of the land area in the study area, and to avoid computational errors, Fishing Cat occurrence points from Sri Lanka were omitted from the LCC analysis.

In addition, a circuit theory-based connectivity analysis was also performed using the tool Circuitscape v4.0 (McRae et al., 2013), which implements the circuit and random walk theory (McRae et al., 2009). This tool computes a resistance-based connectivity metric based on a series of combinatorial and numerical analyses (Shah and McRae, 2008). The prime difference between a circuit and an LCP is that the circuit corridor is identified after computation of multiple paths between the population cores and the conductive probability of every raster cell is measured. In contrast, the LCP is based on a single least-cost route (Bowman et al., 2020). The circuit theory accommodates the assumption that animals may not have the knowledge of the perfect least-cost route (Marrotte et al., 2017) and the most traversed paths could be a cumulative outcome of the paths with minimum resistance. We used Protected Areas (PAs) where Fishing Cat occurrences for T₂ were recorded as core areas indicating source populations. Pair-wise nodes and eight-cell window were parameterised for estimation of current flow, using the inversed ESDM as the resistance surface.

To pinpoint areas with very high density of both current flow and LCPs, i.e. the pinch points for Fishing Cat movement in the study region, the ‘Pinch Point Mapper’ tool (McRae, 2012) from the ‘Linkage Mapper’ toolkit for ArcMap (McRae and Kavanagh, 2011) was used. The Pinch Point mapper combines the frameworks of LCP and circuit theory and identifies pinch points having high density of paths represented through both the LCPs and Circuitscape based current flows. The pinch points are the bottlenecks in the corridor with considerable traffic of animal movement (McRae, 2012). These are regions with degraded or semi-degraded adjacent cells and thus points of significant importance for movement/dispersal from the landscape conservation perspective. Being narrow sections in the corridor, removal of these regions might hamper the connectivity of populations in a landscape (Liu et al., 2020). Linkage paths were constructed using the ‘Linkage Pathways’ tool, which were further used as inputs to the Pinch Point Mapper tool. Pairwise calculation was set for the Circuitscape mode and 4.6 km was set as the minimum cost-weighted corridor width. Since, all raster data in this study were processed at a spatial resolution of 2.5 minutes (~ 4.6 km), this was the lowest possible corridor width that could be parameterised.

2.6 Priority Conservation Units

A conservation unit of 100 km² was assumed for prioritization of landscape conservation units (LCUs) for Fishing Cat. The LCU prioritization was implemented through the R package ‘prioritizr’ (Hanson et al., 2018), using ‘Lsymphony’ open source solver. We used two different scenarios for modelling the LCUs – (a) costs based on FC connectivity and (b) costs based on urbanisation in the landscape. For the first scenario, the connectivity cost values from the LCP output raster and the inversed current flow raster were added and attached to each grid, to designate the costs that FC would incur in a given grid. These costs were calculated from the perspective of identifying the most suitable units for FC. For the urbanization scenario, the raster values from night-time lights and LST were combined and attached to the grids, representing the conservation costs that would be incurred if a given 100 km² grid was to be selected for conservation. The raster output from the ESDM for UrbT₂ and the CIFOR wetlands were used as feature layers.

Optimization targets ranging from 10%-50% of the landscape, with increments of 5% were implemented for each scenario resulting in nine solutions for each respective scenario. Prioritization importance scores (PIS) were assigned to each solution in the inverse order of their target optimization. A PIS of 50, 45, 40, 35, 30, 25, 20, 15 and 10 was assigned to solutions of targets 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50% respectively (Rodewald et al., 2019). Hereafter, the solutions from all the nine prioritized targets were added into a single solution and units encompassing protected areas were selected.

3. Results

3.1 Global distribution of Fishing Cat and limiting factors

Wetlands (18.36%) and elevation (17.15%) were the highest contributing variables determining the ecological niche of Fishing Cat. The felid was predicted to be mainly restricted to low-elevation (<111 m above sea level) wetlands. These wetlands are part of the floodplains and delta regions of the Indus Basin, Ganges-Brahmaputra Basin (GBB), Ayeyarwaddy Basin, Salween Delta, Chao Phraya river system, Mekong Basin and Red River Delta (Fig. 3). In peninsular India, Fishing Cat was mainly predicted to occur in the Mahanadi Basin and the Godavari-Krishna Delta. The Lower Indus Basin and Middle Indus Basin constituting the westernmost limit of Fishing Cat's distribution is predicted to have very high quality Fishing Cat habitat. Our model predicted the occurrence of Fishing Cat along the Indian western coast but the felid might have never occurred there (see Janardhan et al., 2014). Apart from this, the island country of Sri Lanka was predicted to have broad and continuous suitable areas for the cat along both the eastern and western coast. A narrow zone fringing the northern coastline of Java, another island, was also found to be suitable. Among these, the Indus Basin, parts of the Indo-Nepal Terai, Sunderbans delta along with low-elevation wetlands of the Gangetic floodplains, parts of the Mahanadi basin including Chilika lagoon, Bhitarkanika and Mahanadi mangroves and small portions of the Godavari- Krishna delta are predicted to have very highly suitable habitat. In South East Asia, such high quality habitats are sparingly present in the Ayeyarwady delta and coastlines of Thailand, Cambodia and Vietnam. More than 90% of the predicted suitable range for Fishing Cat lies outside protected areas (see Supplementary information, S1). To guide future surveys, we have provided detailed biogeographical information of regions with >50% predicted presence of Fishing Cat in the mainland and separately for the island country of Sri Lanka along with jurisdictional boundaries to maximize relevance for management (see Supplementary information, S2).

3.2 Temporal loss of habitat

The ecological scenario (EcoT1) is a hypothetical one, useful in visualizing the extent of the suitable habitat for Fishing Cat with only natural predictors and without anthropogenic pressures. Since the bioclimatic and topographic factors remained constant over the two time points (T1 and

T2) in this study, a decline of 18% (Table 2) in the suitable habitat under the ecological change scenario (EcoT1 to EcoT2) indicates a shrink in the vegetation cover/habitat, which indirectly represents anthropogenic pressure. On the other hand, the urban impact scenario (UrbT1 to UrbT2) includes proxies of anthropogenic structures as an influencing variable in the model and can better emphasize the impact of urbanization on Fishing Cat habitat.

The ESDM probability maps that were generated using the selected algorithms, RF and SVM, had the Receivers Operating Curve (ROC) evaluation score above 0.82 and Kappa evaluation score above 0.64 for all the computed scenarios (Table 1). This indicates that we could successfully implement the models in estimating the suitable habitat for Fishing Cat in the two scenarios considered in this study. The binary ESDM maps were generated using the respective threshold values for each scenario (Table 1).

Area of the model predicted suitable area for Fishing Cat in each scenario was calculated (Table 1) and the changes in the predicted presence between T₁ and T₂ in both the ecological and urban impact scenarios were calculated (Table 2). The loss of predicted suitable area (Table 2) for Fishing Cat, in the ecological scenario (EcoT₁ to EcoT₂) was estimated at 18.404% and 23.784% in the urban scenario (UrbT₁ to UrbT₂) (see Fig 5 and 6). Simultaneously, percent gain in suitable habitat was also estimated, 4.159% for EcoT₁ to EcoT₂ and 19.375% for UrbT₁ to UrbT₂ (Table 2).

3.3 Landscape connectivity

The raster values of connectivity outputs i.e., the LCC, LCC line density; the Circuitscape output for cumulative current density and the Pinch-points were rescaled to 0-1. The lowest 30% of the cost values in the LCC were used to depict the LCC for Fishing Cat, and the highest 30% of the values to show the density of LCPs in the LCC (Fig. 7). Similarly, top 30% of the maximum flow values (Jennings et al., 2020; Li et al., 2020) were considered to depict the conductivity-based corridor for Fishing Cat movement (Fig. 8) and 5% of the highest values of the output from the Pinch Point Mapper were used as thresholds for delineating the pinch points (Fig. 9).

3.4 Landscape Conservation Units

In both the Fishing Cat connectivity scenario and the least urban scenario, the Indus basin and parts of GBB in South Asia figured as LCUs of very high priority.

According to the Fishing Cat connectivity scenario, 39 high to very high LCUs were found in South Asia. No high priority LCU was present in South-east Asia. Six LCUs of moderate priority were selected in South-east Asia. In the least urban scenario, 25 LCUs of high to very high priority were selected in South Asia. Six LCUs of high to very high priority were present in South-east Asia.

4. Discussion

To the best of our knowledge, this study was the first attempt to model the global distribution of Fishing Cat, an under-studied, globally endangered freshwater mammalian carnivore of high conservation and research value (Veron et al., 2008; Tensen, 2018; Zanin and Neves, 2019). RF and SVM, selected as the best performing algorithms for the SDM of Fishing Cat, have been found to be powerful classifiers in other studies too (Fukuda et al. 2013; Thahn Noi and Kappas, 2018). The felid was predicted to be mainly restricted to low-elevation (<111 m above sea level) wetlands of South and South East Asian river basins (Fig 3). Low elevation was also estimated to be an important predictor for Fishing Cat distribution in the Indian subcontinent (Silva et al., 2020). South Asia holds the core of the global Fishing Cat population with India sharing two trans-boundary regions in the GBB of high Fishing Cat occurrence probability (>80%) - a) wetlands of the Terai region with Nepal, and, b) the Gangetic Delta (including the Sunderbans) with Bangladesh. South Asia also has the highest numbers of LCUs in parts of the GBB and the Indus Basin (Fig 9, Table 3). The situation in South-east Asia seems precarious and therefore worthy of intensive research and conservation efforts. Along the coastline of Myanmar and Thailand, Fishing Cat connectivity is predicted to face the highest resistance but some areas of the Mekong floodplains and delta region provide lower resistance, higher habitat suitability including the presence of LCUs and potentially important dispersal corridors.

4.1 Flexibility/limitedness of its fundamental niche

There are some departures from the hypothetical situation presented by our models as is expected, discussing which might resolve doubts and strengthen our understanding of its ecology and fundamental niche. For example, despite our predictions of the restriction of its niche to low-elevation wetlands (>111 m above sea level), Fishing Cats were documented from an elevation of 1870 m from Sri Lanka's central hilly region. This is the only unit globally to colonize higher elevations and thus constituted a small fraction of the occurrence points in comparison to the regional species pool of the mainland. Therefore this was not chosen as a suitable habitat by our model. A closer introspection of the Sri Lankan geography reveals that freshwater sources in the island originate from the central hilly regions and flow out towards all directions, creating numerous water-rich habitat/wetland complexes throughout the island. Thus, during sea-level rise events, low-elevation populations might have been pushed to migrate up the hills due to geometric constraints imposed by the island and would have been facilitated to colonize the higher altitudes because of the presence of rivers. This could have caused a local adaptation in the Sri Lankan population and effectively extended its fundamental niche. Theoretical predictions do predict selection of broader niche breadth in species in variable environments (Levins, 1962; Sultan and Spencer, 2002). Mainland populations situated in more predictable environments may have been relaxed of such selection pressures. Additionally the presence of more competitors in the mainland might have limited them to a narrower and specialized niche. In addition, Fishing Cat was recorded from drier regions in Sri Lanka, also predicted to be unsuitable/sub-optimal by

our model. The presence of man-made wetlands such as ancient hydrological tanks, reservoirs and croplands simulating Fishing Cat habitat might have facilitated its occurrence in these drier regions inland. Infact, annual rainfall was found to be the most important climatic variable determining Fishing Cat distribution in a Sri Lanka specific modeling (Thudugala, *in litt.*) that might be playing a critical role in maintaining these wetlands in the drier inland regions.

Fishing Cat has also been recorded recently from the much drier central and north-western Indian landscapes (Sadhu and Reddy, 2013; Talegaonkar et al., 2018; Dey, 2018; Dutta et al., 2021) and the arid Deserts and Xeric Shrublands terrestrial ecoregion of Pakistan (Roberts, 1997). Our model predicts the presence of sup-optimal habitat in central and north-western India that has riverine connections to the highly suitable Terai region. Therefore Fishing Cat populations here could be an extension of the Terai population. However, these could be dead ends as they meet the Thar Desert to the west and the highlands and plateau regions of Central India to the south. Nonetheless they represent threatened freshwater ecosystems worthy of attention. In Pakistan, which is the westernmost limit of global Fishing Cat distribution, it is the presence of the Lower and Middle Indus freshwater ecoregions (see Abell et al., 2008), within the drier terrestrial ecoregion that has made this region highly suitable for Fishing Cat with several priority conservation units. Thus records of Fishing Cat from drier regions suggest that either these are marginal habitat or that climatic and geographic factors have contributed to the formation and persistence of wetlands within the drier regions which facilitated the cat to colonize these regions.

Thirdly, our model predicts Fishing Cat occurrence in the Indian western coast which is dominated by the Western Ghats mountain range and associated streams. There are no confirmed reports of the cat's occurrence here historically. Recent surveys have been unable to detect the cat in the western coast, following which it was hypothesized that the salinity of the Arabian Sea could have been the limiting factor (Janardhan et al., 2014). We suggest that rather than salinity, the absence of river systems forming extensive floodplains and deltas in this region, is responsible for Fishing Cat's inability to colonize it. Presence of such riverine systems can overcome limitations imposed by salinity, as is found in the Indus delta region, which meets the Arabian Sea to the south.

Fourthly, our model predicted a gain of 19% habitat between 2010 to 2020 (Table 2). This predicted gain is a result of the significant number of occurrence points in the proximity of urban areas. Such landscapes, which are by-products of rapid urbanization replacing wetland habitat are neither non-habitat, nor fully suitable ones, where the cat has no choice but to persist in remaining small patches. Such landscapes thus exhibit an extremely complicated mosaic of available habitat and built-up spaces, making it difficult for the model to distinguish between pure habitat and mixed/non-habitat, leading to counter-intuitive predictions suggesting habitat gain. For instance, in Colombo, Sri Lanka, GPS-collared adult females were found to use wetland areas more than urban areas whereas a sub-adult male was found to exclusively use hyper-urban areas within the city suggesting that it was pushed into marginal habitat by adults (Ratnayaka et al., 2021). These hyper-urban areas, as observed by us, were characterized by abandoned colonial architectures replete with anthropogenic food sources such as fish present in large courtyard ponds, commensal rodents and birds present in the unkempt gardens. However, all urban spaces, especially upcoming modern smart cities do not/will not have heritage buildings and their unmanicured open spaces, which is why the gain shown by our model cannot be ecologically supported. Moreover, road kills and negative interactions between humans and Fishing Cat are commonly occurring issues in rapidly urbanizing landscapes (Adhya et al., 2011; Thudugala, 2015; Ganguly et al., 2020; Thudugala *in litt*). In Sri Lanka alone, data from a citizen science program (2005 to 2021) shows 101 records of cat death/injury from vehicular collisions. This further suggests that urban spaces might infact be ecological traps in the long term.

4.2 Research and conservation efforts needed outside PA network

According to model predictions, more than 90% of the predicted Fishing Cat distribution lies outside protected areas. However, qualitative and/or quantitative assessments of populations and their threats outside protected areas in range countries remain woefully scarce. The few studies that have been conducted on the felid largely report sporadic occurrences and status reports that either lacked rigor, comprehensiveness and/or placement within the larger biogeographic context (Adhya and Dey, 2011; Mukherjee et al., 2012; Palei et al., 2018; Chutipong et al., 2019; Kantimahanti et al. 2019; Kolipaka et al., 2019; Chakraborty et al., 2020). Population estimates on the species are very scarce and restricted to a few protected areas (Nair, 2012; Das et al., 2017) with the exception of Phosri et al., 2021. Across South Asia, it is the freshwater landscapes outside protected areas that seem to be important for maintaining connectivity but are being subjected to severe degradation. Large portions of the Indus, wetlands of the Gangetic Plains, particularly in Bangladesh, the Terai-Dooars region, wetland complexes of the Brahmaputra and coastal wetlands of the Indian eastern coast between Chilika lagoon and the southernmost Indian Fishing Cat population in Godavari-Krishna delta need intensive surveys to not only determine current status but also to examine present connectivity using advanced genetic tools. The Indus population deserves special mention as a region that holds the westernmost population of Fishing Cat globally, is predicted to have highly suitable areas important for conservation, but could well be suffering from isolation effects. Roberts (1977), had reported occasional stragglers from the Middle Indus

Basin, and, along the floodplains of the rivers Sutlej, Beas and Ravi in the adjacent Indian Punjab district. A thorough comprehensive current assessment is needed in the region.

The distribution of the species in most of South-east Asia has been extremely hampered in the recent past. We recommend thorough investigations and rapid conservation efforts to stem the loss of low-elevational wetlands like mangroves and marshes in the pinch points of connectivity. The species has been detected in the Ayeyarwady region of Myanmar (Lin and Pratt, 2019). Targeted surveys are required in the adjacent Salween Basin which has moderately suitable habitat. In Thailand, Fishing Cat has been detected in the Chao Phraya river system region (Chutipong et al., 2019) and from peninsular Thailand (Cutter, 2007). More investigations are recommended in the inland and coastal wetlands present in the country's eastern and western coastal provinces (see S1), especially around the Krabi estuary, even though Chutipong et al., (2019), failed to detect them in this area. In Cambodia, Fishing Cat populations were found to be restricted to the mangrove forests of Peam Krasop Wildlife Sanctuary and Ream National Park but not in Botum Sakor National Park (Thaung et al., 2018). Longer, more intensive and targeted surveys focussed in coastal wetlands of Cambodia as well as along shoreline mangrove patches, for example, in the Koh Kong Krov island are needed. Inland wetlands along the Mekong river in Cambodia should also be targeted for further surveys. A dead specimen retrieved from a roadside market in the Tonle Sap area in 2018, indicates the possibility of an existing population there (Ministry of Agriculture Forestry and Fisheries and Wildlife Alliance *pers. comm.*, 2018) as was previously assumed (Davidson et al., 2006; Rainey and Kong, 2010), prompting surveys currently underway. In Vietnam, where surveys have failed to detect Fishing Cat in recent decades, we recommend targeted surveys in the Plain of Reeds, Red River Delta and U Minh wetlands. Part of U Minh consists of peat swamps which might not be preferred by Fishing Cat but parts with swamps and grasslands could be potentially important survey sites. In Java, there is evidence of the cat's presence historically (Sody, 1936) and more recently (Duckworth *pers. comm.*, 2012) corroborating model findings. However, surveys have failed to re-detect it since the last decade suggesting that the species is critically endangered in the country (Willianto *pers. comm.*, 2021). No suitable habitat for Fishing Cat was predicted to be present in Sumatra. This is backed by absence of either historical or recent evidence of its presence in the country. How the Fishing Cat came to occur in Java therefore is a mystery.

4.3 Loss of critical wetland habitat

Our models predict a contraction of more than 23.74% in suitable Fishing Cat habitat between the two time periods T1 and T2 due to urbanization. This is relatable given the continuing trend in rapid wetland loss globally and especially in Asia (Davidson, 2018). Wetlands are predicted to disappear much faster given the projected increase of urban population by 1.4 billion within 2050 (Hettiaracchi et al. 2015). Moreover, ephemeral or intermittently flooded wetlands are not well-represented in global datasets (Davidson, 2014), which are known to be habitat preferred by

Fishing Cat, such as reed-building marshes, mangrove swamps and freshwater swamps (Sunquist and Sunquist, 2014; Mukherjee et al., 2016; Hunter et al., 2019). This further augments the threat to Fishing Cat as loss of their primary habitat due to urbanization is undoubtedly rapid but has remained undetected and therefore not foregrounded.

Human populations are known to be concentrated in productive lowland regions of the world and undoubtedly it is here that the impact of sustaining modern industrial human societies are most strongly felt (Darwall and Freyhof, 2016). Coastal wetlands have been more severely affected by urbanization and its indirect effects than inland natural wetlands (Wilkinson et al., 1994; Davidson, 2018). For instance, continuous development pressures have been degenerating the Indo-Malayan mangroves with several stretches in coastal South and South-east Asia annihilated to create megacities (Dasgupta and Shaw, 2013; Kumar and Ambastha, 2018). The loss has exacerbated in the last few decades rendering mangroves in the Indus, Ayeryarwady, Mekong and Red river basins critically degraded with the Lower Indus Basin losing 43% of its mangrove cover from 1990 to 2014 and Ayeyarwady delta losing 64% from 1978 to 2011 with predictions of complete deforestation by 2026 (Dasgupta and Shaw, 2013; Webb et al., 2014; Richard and Freiss, 2016; Qasim et al., 2016). Commercial shrimp culture is a particularly severe threat to the coastal wetlands of South-east Asia destroying 41% of Thailand's coastal mangroves and 50% of Mekong delta's mangroves since 1975 (Dasgupta and Shaw, 2013). Wetlands along the Indian east coast formed by Mahanadi, Godavari and Krishna have also been affected by hydrological fragmentation and dams with recent studies estimating a decline in the Godavari-Krishna delta by 42 km² between 1977 and 2008 (Kumar and Patnaik, 2018; Day et al., 2019). Mangroves in this region were found to be under high stress from intensive aquaculture and industrialization (Day et al., 2019; Bagaria et al., 2021). In addition, 42% riparian vegetation has also been lost in the Lower Indus Basin from 1990 to 2014 (Webb et al., 2014). In the Terai Arc Landscape shared between Nepal and India, much of the wet grasslands and swamps were converted during 1970-80 for agricultural expansion and human settlements with only patches of disjunct habitat persisting in protected areas (Chanchani et al., 2014). A further loss of natural grassland area by 24% was estimated from 1980-2000 across eight protected areas in India and Nepal (Banerjee et al., 2020). In this context, lowlands in GBB which were suggested to be a probable climate refugia for the species by Silva et al. 2020, maybe rendered unsuitable if the present rates and types of alteration continue. According to the Asian Wetland Directory (1989), 68% of Sri Lanka's 41 internationally significant wetland sites are under moderate to high threat. The Dry Zone's coastal lagoons, estuaries, and mangrove swamps are highly threatened due to various developmental activities. The Mahaweli Ganga Floodplain System has been recognized as a wetland site 'under significant threat of destruction', and is comparable with the Sundarbans and Mekong Delta, demanding immediate action (IUCN Sri Lanka, 2004). In the light of these recent and rapid changes, we further stress the criticality of the status of Fishing Cat worldwide. This is because range reduction is known to imply population declines (IUCN Standards and Petitions Subcommittee, 2017; Ceballos et al., 2017; Santini et al., 2019).

4.4 Priority regions and threats

While spatial prioritization for conservation research and action has foregrounded biodiversity in the global context and eased the process of systematic planning and fund acquisition (Myers, 2003), it has also been substantially criticized for being bereft of ‘situated knowledge’ and its failure to engage with locally obtained experience (Wyborn and Evans, 2021). In our study, we attempted to interpret and discuss the findings of our model based on our collated local and regional work experience. Most of the authors are members of Fishing Cat Conservation Alliance, a global cohort of researchers and conservationists, working to facilitate change across the range countries.

Our findings suggest that GBB, consisting of wetlands in the Terai region, Gangetic plains, Gangetic Delta and valleys of the Brahmaputra along with its tributaries and distributaries, have areas with high occurrence probabilities of Fishing Cat (>80%) and might be playing a critical role in maintaining connectivity between populations within South Asia barring the island country of Sri Lanka. The populations in the Terai and Sundarbans were in fact found to be genetically connected in the past (Mukherjee et al., 2015). This implies that populations in GBB are integral to maintaining connectivity between transboundary regions connecting Nepal, Bangladesh and India. Due to its strategic position, GBB is probably indispensable in preventing isolation of populations in the Lower and Middle Indus Basin and those that are located in the Indian East coast populations. Secondly, the Gangetic Delta of GBB is critical in maintaining connectivity between populations in South and South-east Asia, since it is contiguous to the coastal wetlands of Myanmar. Additionally, GBB had the highest number of LCUs, many of which are contiguous, suggesting that this region provides high permeability conducive for species dispersal and requires lesser investments for conservation and restoration of the species’ habitat (Table 3). The Lower Indus Basin had the second highest number of LCUs (Table 3). Even though our connectivity analysis shows that Beas, Ravi and Sutlej floodplains provide limited resistance, this is unlikely given the uninhibited loss of wetlands in the Indian state of Punjab following the Green Revolution and urbanization (Brar and Chandel, 2012). A limitation of our study is the use of only an urbanization based resistance matrix for assessing connectivity, which under-represents the accumulated resistance to dispersal from hostile land-use regimes such as extensively occurring intensive agricultural landscapes and similar aquaculture waterscapes.

The river basins with predicted Fishing Cat occupancy are also among the biggest freshwater fish producing regions with the Ganges, Brahmaputra and Mekong featuring among the top seven basins to contribute to 50% of the global freshwater fish catch, supporting the livelihood of millions locally and providing nutrition globally (WWF, 2021; Ainsworth et al., 2021). These basins are prey-dense wet landscapes for Fishing Cat. Yet these are facing above-average stress levels from the compounding effects of hydropower dams, pollution, overexploitation and climate change resulting in catastrophic declines in wild freshwater fish populations (FAO, 2020; WWF 2021). A third of the world’s freshwater fishes are threatened with extinction and 80 species are already extinct (WWF, 2021). To state that freshwater fishes in the developing Asian economies

are being similarly, if not more severely affected, will not be an overstatement. Throughout its global distribution range, 90% of which lies outside the purview of protection, Fishing Cat faces the dual challenge of severe habitat and prey loss. It is here that wetlands are being subjected to diversion to meet development objectives. For instance, in India, these are categorized as ‘wastelands’ (National Remote Sensing Centre, 2010; National Strategic Development Plan, 2014; Hettiaracchi et al. 2015), in contravention of the Ramsar convention and by contradicting national wetlands protection laws (see Wetland Rules, 2020). In Cambodia, on the other hand, regulations can be weakened to develop large swathes of protected areas including mangrove forests to meet economic objectives. The felid was recently downlisted to Vulnerable in 2016 from Endangered in 2010 with the change in the Red List category attributed to improved data quality and not an improved conservation status (Mukherjee et al., 2010; Mukherjee et al., 2016). However, current trends mandate a re-assessment in the light of the species’ critical condition in Java and Vietnam where it remains undetected for the last two decades. In addition, we have most certainly underestimated its range contraction by not accounting for the compounding effects of development-induced intensive resource uses such as agriculture and aquaculture, which as regimes, add to the impacts of urbanization and climate change thereby escalating global threats to its habitat, i.e., freshwater ecosystems.

4.5 A flagship mammal to conserve highly threatened freshwater ecosystems

With research and conservation action mostly having a terrestrial and marine focus, the perspective of freshwater ecosystems have been grossly under-represented, impeding fund allocation and contributing indirectly to their high rates of loss (Tickner et al., 2020). Dearth of basic information such as the distribution and status of many freshwater species has resulted in a lack of focussed broadscale conservation plans (Abell et al., 2008). Given the need to highlight the disproportionately threatened and critical status of freshwater biodiversity, Rees et al., 2020, prescribed the adoption of flagship species to promote and motivate public and political engagement. In this context, Fishing Cat was found to have an above average appeal among the general public despite being restricted in its distribution and niche (Macdonald et al., 2017). Devising range-wide strategies to conserve this hypercarnivore and top predator may benefit the ecological community it represents as well as the critical habitat it inhabits, such as ephemeral wetlands (like marshes, mangroves and freshwater swamps) that are situated outside the purview of protection and are highly abused owing to ill-awareness and apathy. We thus propose that Fishing Cat be used as a flagship species to conserve rapidly degrading low-altitude wetlands and their ecological communities in the major river basins of South and South-east Asia. We emphasize that such conservation has to be socio-ecologically sensitive, inclusive of multiple stakeholders and function within a wise-use operating space (see Kumar et al., 2020), knowing well that the dominant terrestrial strategy of ‘fortress conservation’ is inadequate for freshwater biota conservation (Dudgeon et al., 2006).

Data accessibility

All distributional data needed to evaluate the results and conclusions of the paper are available at www.fishingcat.org.

Declaration of competing interests

The authors declare that they have no conflict of interest.

Author contributions

Conceptualization - Tiasa Adhya, Partha Dey; Data curation - Priyamvada Bagaria; Formal analysis - Priyamvada Bagaria; Funding acquisition - N/A; Investigation - Tiasa Adhya, Partha Dey, Priyamvada Bagaria; Methodology - Priyamvada Bagaria; Project administration - Tiasa Adhya; Resources - Jim Sanderson; Software - Priyamvada Bagaria; Supervision - Tiasa Adhya, Partha Dey; Validation - Tiasa Adhya, Partha Dey, Anya Ratnayaka, Ashan Thudugala, Vanessa Herranz; Visualization - Tiasa Adhya, Partha Dey, Priyamvada Bagaria; Roles/Writing - original draft - Tiasa Adhya, Priyamvada Bagaria, Partha Dey; Writing - review & editing - Tiasa Adhya, Partha Dey, Vanessa Herranz, Anya Ratnayaka, Ashan Thudugala, Aravind N.A.

Acknowledgements

We thank all members of the Fishing Cat Conservation Alliance (www.fishingcat.org) who worked over the years in their respective range countries and improved the quality of data available on the Fishing Cat. This was a collaborative venture where the authors voluntarily engaged to develop the manuscript through a series of online meetings during 2019-2021. This research did not receive any specific grant from funding agencies in the public, commercial and/or not-for-profit sectors. We are thankful to Professor A. Townsend Peterson and Geoff Hyde for their valuable suggestions and comments. We are also grateful to Dr Arjun Srivathsa and Dr Ajith Kumar for their specific inputs.

References

- Abell, R., Thieme, M. L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., ... & Petry, P. (2008). Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. *BioScience*, 58(5), 403-414.
- Adhya, T. (2011). Status survey of fishing cat (*Prionailurus viverrinus*) in Howrah and Hooghly, West Bengal: intermediate report submitted to the Small Grants Programme. WWF. India; [accessed 2021 July 25]. http://awsassets.wwfindia.org/downloads/status_survey_of_fishing_cats.pdf
- Ahmed, N., Atzberger, C., & Zewdie, W. (2021). Species Distribution Modelling performance and its implication for Sentinel-2-based prediction of invasive *Prosopis juliflora* in lower Awash River basin, Ethiopia. *Ecological Processes*, 10(1), 1-16.
- Ainsworth, R., Cowx, I. G., & Funge-Smith, S. J. (2021). A review of major river basins and large lakes relevant to inland fisheries.
- Albert, J.S., Destouni, G., Duke-Sylvester, S.M., Magurran, A.E., Oberdorff, T., Reis, R.E., Winemiller, K.O. and Ripple, W.J., (2020). Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio*, pp.1-10.
- Araujo, M. B., & Guisan, A. (2006). Five (or so) challenges for species distribution modelling. *Journal of biogeography*, 33(10), 1677-1688.
- Araujo, M. B., & New, M. (2007). Ensemble forecasting of species distributions. *Trends in ecology & evolution*, 22(1), 42-47.
- Ariken, M., Zhang, F., Liu, K., Fang, C., & Kung, H. T. (2020). Coupling coordination analysis of urbanization and eco-environment in Yanqi Basin based on multi-source remote sensing data. *Ecological Indicators*, 114, 106331.
- Arthington, A. H. (2021). Grand challenges to support the freshwater biodiversity Emergency Recovery Plan. *Frontiers in Environmental Science*, 9, 118.
- Bagaria, P., Nandy, S., Mitra, D., & Sivakumar, K. (2021). Monitoring and predicting regional land use and land cover changes in an estuarine landscape of India. *Environmental Monitoring and Assessment*, 193(3), 1-27.
- Balian E, Lévêque C, Segers H. (2008). *Freshwater Animal Diversity Assessment*, vol. 595. Springer.

656 Banerjee, S., Das, D. & John, R. (2020). Recent degradation and transformation of grasslands in
657 the Terai ecosystems of the Indian subcontinent. In *EGU General Assembly Conference Abstracts*
658 (p. 6295).

659 Barbet-Massin, M., Jiguet, F., Albert, C. H., & Thuiller, W. (2012). Selecting pseudo-absences for
660 species distribution models: how, where and how many?. *Methods in ecology and evolution*, 3(2),
661 327-338.

662 Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O. U., Swartz, B., Quental, T. B., ... Ferrer,
663 E. A. (2011). Has the Earth's sixth mass extinction already arrived? *Nature*, 471, 51– 57.
664 <https://doi.org/10.1038/nature09678>

665 Boitani, L., Maiorano, L., Baisero, D., Falcucci, A., Visconti, P., Rondinini, C., (2011). What
666 spatial data do we need to develop global mammal conservation strategies? *Philos. Trans. R. Soc.*
667 *B Biol. Sci.* 366, 2623–2632. <https://doi.org/10.1098/rstb.2011.0117>

668 Biega, A. M., Lamont, M., Mooers, A., Bowkett, A. E., & Martin, T. E. (2019). Guiding the
669 prioritization of the most endangered and evolutionary distinct birds for new zoo conservation
670 programs. *Zoo biology*, 38(3), 305-315.

671 Bowman, J., Adey, E., Angoh, S. Y., Baici, J. E., Brown, M. G., Cordes, C., ... & Solmundson, K.
672 (2020). Effects of cost surface uncertainty on current density estimates from circuit theory. *PeerJ*,
673 8, e9617.

674 Brar, K. K., & Chandel, V. B. S. (2012). The lost natural Wetlands of Punjab (India): an inventory.
675 *Journal of the Indian Society of Remote Sensing*, 40(1), 97-107.

676 Brown, J. L. (2014). SDM toolbox: a python-based GIS toolkit for landscape genetic,
677 biogeographic and species distribution model analyses. *Methods in Ecology and Evolution*, 5(7),
678 694-700.

679 Brown, J. L., Bennett, J. R., & French, C. M. (2017). SDMtoolbox 2.0: the next generation Python-
680 based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses.
681 *PeerJ*, 5, e4095.

682 Burivalova, Z., Butler, R.A. and Wilcove, D.S., (2018). Analyzing Google search data to debunk
683 myths about the public's interest in conservation. *Frontiers in Ecology and the Environment*, 16(9),
684 pp.509-514.

685 Ceballos, G., Ehrlich, P.R., Dirzo, R., (2017). Biological annihilation via the ongoing sixth mass
686 extinction signaled by vertebrate population losses and declines. In: *Proceedings of the National*
687 *Academy of Sciences of the United States of America* 114, pp. E6089eE6096. National Academy
688 of Sciences. Available from. <http://www.ncbi.nlm.nih.gov/pubmed/28696295>.

689 Chakraborty, S., Barik, S., Saha, R., Dey, A., Deuti, K., Venkatraman, C., Mazumdar, S. and Saha,
690 G.K., (2020). Camera-trap records of Fishing Cat (*Prionailurus viverrinus*) from East Medinipur
691 (West Bengal, India), and notes on threats to this population. *Écoscience*, 27(3), pp.149-156.

692 Chan, L. M., Brown, J. L., & Yoder, A. D. (2011). Integrating statistical genetic and geospatial
693 methods brings new power to phylogeography. *Molecular phylogenetics and evolution*, 59(2),
694 523-537.

695 Chanchani, P., Lamichhane, B. R., Malla, S., Maurya, K., Bista, A., Warriar, R., ... & Borah, J.
696 (2014). Tigers of the Transboundary Terai Arc Landscape: Status, distribution and movement in
697 the Terai of India and Nepal. *National Tiger Conservation Authority, Government of India, and*
698 *Department of National Park and Wildlife Conservation, Government of Nepal NTNC/DNPWC*, 3.

699 Chutipong, W., Kamjing, A., Klinsawat, W., Ngoprasert, D., Phosri, K., Sukumal, N., Wongtung,
700 P. and Tantipisanuh, N., (2019). An update on the status of fishing cat *Prionailurus viverrinus*
701 Bennett, 1833 (Carnivora: Felidae) in Thailand. *Journal of Threatened Taxa*, 11(4), pp.13459-
702 13469.

703 Collen B, Turvey ST, Waterman C, Meredith HMR, Kuhn TS, Baillie JEM, Isaac NJB. (2011).
704 Investing in evolutionary history: implementing a phylogenetic approach for mammal
705 conservation. Philosophical Transactions of the Royal Society B: Biological Sciences 366:2611–
706 2622.

707 Cutter, P. (2007). Surveys for Fishing Cat (*Prionailurus viverrinus*) in Thale Noi Non-Hunting
708 Area, Pattalung Province, Thailand, May 2006 - February 2007. Report: 1-25. Report to
709 Smithsonian's National Zoological Park and Cincinnati Zoo.

710 Cutter, P. (2015). Fishing cat ecology: food habits, home ranges, habitat use and mortality in a
711 human-dominated landscape around Khao Sam Roi Yot, Peninsular Thailand. Master of Science
712 Thesis submitted to the University of Minnesota.

713 Darwall, W. R., & Freyhof, J. Ö. R. G. (2016). Lost fishes, who is counting? The extent of the
714 threat to freshwater fish biodiversity. *Conservation of freshwater fishes*, 1-36.

715 Das, S. K., Saha, R., Mukherjee, S., Danda, A., & Borah, J. (2017). First estimates of fishing cat
716 abundance and density in Lothian Wildlife Sanctuary, Sundarbans, India. *Cat News*, 66, 25-27.

717 DasGupta, R., & Shaw, R. (2013). Cumulative impacts of human interventions and climate change
718 on mangrove ecosystems of South and Southeast Asia: an overview. *Journal of Ecosystems*, 2013.

719 Davidson, N. C. (2014). How much wetland has the world lost? Long-term and recent trends in
720 global wetland area. *Marine and Freshwater Research* 65, 934–941. doi:10.1071/MF14173

Davidson, N. C., Fluet-Chouinard, E., & Finlayson, C. M. (2018). Global extent and distribution of wetlands: trends and issues. *Marine and Freshwater Research*, 69(4), 620-627.

Davidson, P. J. (2006). The biodiversity of the Tonle Sap Biosphere Reserve: 2005 status review. *Wildlife Conservation Society (unpublished report to UNDP/GEF Tonle Sap Conservation Project), Phnom Penh*.

Day, J.W., Ramachandran, R., Giosan, L., Syvitski, J. and Kemp, G.P., (2019). Delta winners and losers in the Anthropocene. In *Coasts and Estuaries* (pp. 149-165). Elsevier.

Dixon, M. J. R., Loh, J., Davidson, N. C., Beltrame, C., Freeman, R., and Walpole, M. (2016). Tracking global change in ecosystem area: the Wetland Extent Trends index. *Biological Conservation* 193, 27–35. doi:10.1016/J.BIOCON.2015.10.023

Duckworth, J. W., Shepherd, C. R., Semiadi, G., Schauenberg, P., Sanderson, J., Robertson, S. I., ... & Brickle, N. W. (2009). Does the fishing cat inhabit Sumatra. *Cat News*, 51, 4-9.

Duckworth, J. W., Stones, T., Tizard, R., Watson, S., & Wolstencroft, J. (2010). Does the fishing cat inhabit Laos. *Cat News*, 52, 4-7.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.H., Soto, D., Stiassny, M.L. and Sullivan, C.A., (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews*, 81(2), pp.163-182.

Dudgeon, D. (2019). Multiple threats imperil freshwater biodiversity in the Anthropocene. *Current Biology*, 29(19), R960-R967.

Duncan, C., Nilsen, E. B., Linnell, J. D., & Pettorelli, N. (2015). Life-history attributes and resource dynamics determine intraspecific home-range sizes in Carnivora. *Remote Sensing in Ecology and Conservation*, 1(1), 39-50.

FAO (2020) The State of Food and Agriculture 2020. Overcoming water challenges in agriculture. Rome.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., ... & Snyder, P. K. (2005). Global consequences of land use. *science*, 309(5734), 570-574.

Fukuda, S., De Baets, B., Waegeman, W., Verwaeren, J., & Mouton, A. M. (2013). Habitat prediction and knowledge extraction for spawning European grayling (*Thymallus thymallus* L.) using a broad range of species distribution models. *Environmental modelling & software*, 47, 1-6.

751 Ganguly, D. (2020). Fishing Cat mortality outside protected areas in West Bengal, India, 2019-20.
752 *Cat News*, 71, 27-29.

753 Gardner, R.C. and Finlayson, C., (2018). October. Global wetland outlook: state of the World's
754 wetlands and their services to people. In *Ramsar Convention Secretariat* (pp. 2020-5).

755 Gittleman, J. L., & Harvey, P. H. (1982). Carnivore home-range size, metabolic needs and ecology.
756 *Behavioral Ecology and Sociobiology*, 10(1), 57-63.

757 Gumbs R, Gray CL, Wearn OR, Owen NR. (2018). Tetrapods on the EDGE: Overcoming data
758 limitations to identify phylogenetic conservation priorities. PLoS ONE 13:1–19.

759 Gui, X., Wang, L., Yao, R., & Yu, D. (2019). Investigating the urbanization process and its impact
760 on vegetation change and urban heat island in Wuhan, China. *Environmental Science and Pollution*
761 *Research*, 26(30), 30808-30825.

762 Guisan, A., & Thuiller, W. (2005). Predicting species distribution: offering more than simple
763 habitat models. *Ecology letters*, 8(9), 993-1009.

764 Hao, T., Elith, J., Guillera-Aroita, G., & Lahoz-Monfort, J. J. (2019). A review of evidence about
765 use and performance of species distribution modelling ensembles like BIOMOD. *Diversity and*
766 *Distributions*, 25(5), 839-852.

767 Haque NM, Vijayan V. (1993). Food habits of the fishing cat *Felis viverrina* in Keoladeo National
768 Park, Bharatpur, Rajasthan. *J Bombay Nat Hist Soc*. 90:498–500

769 Hong, H. T. C., Avtar, R., & Fujii, M. (2019). Monitoring changes in land use and distribution of
770 mangroves in the southeastern part of the Mekong River Delta, Vietnam. *Tropical ecology*, 60(4),
771 552-565.

772 Hortal, J., de Bello, F., Diniz-Filho, J.A.F., Lewinsohn, T.M., Lobo, J.M., Ladle, R.J., (2015).
773 Seven shortfalls that beset large-scale knowledge of biodiversity. *Annu. Rev. Ecol. Evol. Syst.* 46,
774 523–549. <https://doi.org/10.1146/annurev-ecolsys-112414-054400>.

775 Hou, W., & Hou, X. (2020). Spatial–temporal changes in vegetation coverage in the global coastal
776 zone based on GIMMS NDVI3g data. *International Journal of Remote Sensing*, 41(3), 1118-1138.

777 Hunter, L. (2019). *Carnivores of the world* (Vol. 117). Princeton University Press.

778 IUCN Standards, Petitions Subcommittee, (2017). Guidelines for using the IUCN red list
779 categories and criteria. Available from. [http://intranet.iucn.org/](http://intranet.iucn.org/webfiles/doc/SSC/RedList/RedListGuidelines.pdf)
780 [webfiles/doc/SSC/RedList/RedListGuidelines.pdf](http://intranet.iucn.org/webfiles/doc/SSC/RedList/RedListGuidelines.pdf).

781 Isaac NJB, Turvey ST, Collen B, Waterman C, Baillie JEM. (2007). Mammals on the EDGE:
782 Conservation Priorities Based on Threat and Phylogeny. *PLoS ONE* 2:e296.

783 Jalkanen, J., Toivonen, T., & Moilanen, A. (2020). Identification of ecological networks for land-
784 use planning with spatial conservation prioritization. *Landscape Ecology*, 35(2), 353-371.

785 Janardhanan, R., Mukherjee, S., Karunakaran, P. V., & Athreya, R. (2014). On the occurrence of
786 the fishing cat *Prionailurus viverrinus* Bennet, 1833 (Carnivora: Felidae) in coastal Kerala, India.
787 *Journal of Threatened Taxa*, 6(3), 5569-5573.

788 Jerdon, T. C. (1874). The mammals of India: a natural history of all the animals known to inhabit
789 continental India. J. Wheldon.

790 Jiménez-Valverde, A., & Lobo, J. M. (2007). Threshold criteria for conversion of probability of
791 species presence to either–or presence–absence. *Acta oecologica*, 31(3), 361-369.

792 Johnson, W. E., Eizirik, E., Pecon-Slaterry, J., Murphy, W. J., Antunes, A., Teeling, E., & O'Brien,
793 S. J. (2006). The late Miocene radiation of modern Felidae: a genetic assessment. *Science*,
794 311(5757), 73-77.

795 Jutzeler, E., Xie, Y., & Vogt, K. (2010). Fishing cat-*Prionailurus viverrinus*. *Cat News*, 5, 48-49.

796 Kantimahanti M., Thyadi A., Chintalapudi A., Vivek R. H. & Yerramsetti P. (2019). Camera trap
797 record of inland fishing cat from east coastal plains of South India. *Cat News* 70, 16–17.

798 Kitchener, A. (1991). *The natural history of the wild cats* (pp. 272-280). Comstock Pub.
799 Associates.

800 Kolipaka, S.S., Srivastava, D.P., Prasad, S. & Rust, N.A., (2019). Fishing cat conservation in hu-
801 man-dominated landscapes in West Bengal, India.

802 Kuhn, M., (2008). Building predictive models in R using the caret package. *Journal of statistical*
803 *software*, 28(1), pp.1-26.

804 Kumar, R., McInnes, R., Finlayson, C. M., Davidson, N., Rissik, D., Paul, S., ... & Fennessy, S.
805 (2020). Wetland ecological character and wise use: towards a new framing. *Marine and*
806 *Freshwater Research*, 72(5), 633-637.

807 Levins R. (1962). Theory of fitness in a heterogeneous environment. I. The fitness set and adaptive
808 function. *American Naturalist* 96:361–373.

809 Lin, N., & Platt, S. G. (2019). Recent photographic records of Fishing Cat *Prionailurus viverrinus*
810 (Bennett, 1833)(Carnivora: Felidae) in the Ayeyarwady Delta of Myanmar. *Journal of Threatened*
811 *Taxa*, 11(7), 13910-13914.

812 Liu, L., & Meng, L. (2020). Patterns of Urban Sprawl from a Global Perspective. *Journal of Urban*
813 *Planning and Development*, 146(2), 04020004.

814 Lin, Y. P., Schmeller, D. S., Ding, T. S., Wang, Y. C., Lien, W. Y., Henle, K., & Klenke, R. A.
815 (2020). A GIS-based policy support tool to determine national responsibilities and priorities for
816 biodiversity conservation. *PloS one*, 15(12), e0243135.

817 Liu, C., Berry, P. M., Dawson, T. P., & Pearson, R. G. (2005). Selecting thresholds of occurrence
818 in the prediction of species distributions. *Ecography*, 28(3), 385-393.

819 Liu, X., Liu, D., Zhao, H., He, J., & Liu, Y. (2020). Exploring the spatio-temporal impacts of
820 farmland reforestation on ecological connectivity using circuit theory: A case study in the agro-
821 pastoral ecotone of North China. *Journal of Geographical Sciences*, 30(9), 1419-1435.

822 Lozano, V. (2021). Distribution of Five Aquatic Plants Native to South America and Invasive
823 Elsewhere under Current Climate. *Ecologies*, 2(1), 27-42.

824 Macdonald, D., & Loveridge, A. (Eds.). (2010). *The biology and conservation of wild felids* (Vol.
825 2). Oxford University Press.

826 Macdonald, E. A., Hinks, A., Weiss, D. J., Dickman, A., Burnham, D., Sandom, C. J., ... &
827 Macdonald, D. W. (2017). Identifying ambassador species for conservation marketing. *Global*
828 *Ecology and Conservation*, 12, 204-214.

829 Marrotte, R. R., Bowman, J., Brown, M. G., Cordes, C., Morris, K. Y., Prentice, M. B., & Wilson,
830 P. J. (2017). Multi-species genetic connectivity in a terrestrial habitat network. *Movement ecology*,
831 5(1), 21.

832 Marquardt, D. W. (1970). Generalized inverses, ridge regression, biased linear estimation, and
833 nonlinear estimation. *Technometrics*, 12(3), 591-612.

834 McRae, B. H., & Kavanagh, D. M. (2011). Linkage mapper connectivity analysis software. *The*
835 *Nature Conservancy, Seattle WA*.

836 McRae, B. (2012). Pinchpoint Mapper User Guide. The Nature Conservancy, Seattle WA.
837 Available at: <http://www.circuitscape.org/linkagemapper>.

838 McRae, B. H., & Shah, V. B. (2009). Circuitscape user's guide. *The University of California, Santa*
839 *Barbara*.

840 McRae, B. H., Shah, V. B., & Mohapatra, T. K. (2013). Circuitscape 4 user guide. The nature
841 conservancy.

842 Ministry of Environment Sri Lanka (2012). The National Red List 2012 of Sri Lanka; Conservation
843 Status of the Fauna and Flora. Ministry of Environment, Sri Lanka.

844 Mishra, R., Basnet, K., Amin, R., & Lamichhane, B. R. (2018). Fishing Cat *Prionailurus viverrinus*
845 Bennett, 1833 (Carnivora: Felidae) distribution and habitat characteristics in Chitwan National
846 Park, Nepal. *Journal of Threatened Taxa*, 10(11), 12451-12458.

847 Mishra, R., Gautam, B., Kaspal, P., & Shah, S. (2021). Population status and threats to fishing cat
848 *Prionailurus viverrinus* (Bennett, 1833) in Koshi Tappu Wildlife Reserve, Eastern Nepal. *Nepalese*
849 *Journal of Zoology*, 5(1), 13-21. <https://doi.org/10.3126/njz.v5i1.38284>

850 Morris, R.C. (1936). The Vernay-Hopwood Upper Chindwin Expedition. *Journal of the Bombay*
851 *Natural History Society* 38: 647–671.

852 Mukherjee, S. (2015). Phylogeography of the Fishing Cat in India. In: A. Appel and J. W.
853 Duckworth (eds.), *Proceedings of the First International Fishing Cat Symposium*, 25-29, Nov,
854 2015, Nepal. FCWG, UK.

855 Mukherjee, S., Appel, A., Duckworth, J.W., Sanderson, J., Dahal, S., Willcox, D.H.A., Herranz
856 Muñoz, V., Malla, G., Ratnayaka, A., Kantimahanti, M., Thudugala, A., Thaung, R. & Rahman,
857 H. (2016). *Prionailurus viverrinus*. *The IUCN Red List of Threatened Species* 2016:
858 e.T18150A50662615.

859 Mukherjee, S., Krishnan, A., Tamma, K., Home, C., Joseph, S., Das, A., & Ramakrishnan, U.
860 (2010). Ecology driving genetic variation: a comparative phylogeography of jungle cat (*Felis*
861 *chaus*) and leopard cat (*Prionailurus bengalensis*) in India. *PloS one*, 5(10), e13724.

862 Myers, N. (2003). *Bioscience* 53, 916–917.

863 Nair, S. (2012). Habitat use and abundance of Fishing Cats (*Prionailurus viverrinus*) from camera
864 trap surveys used for monitoring Tigers in the Terai region of India. MSc Thesis submitted to
865 University of Otago, Dunedin, New Zealand.

866 National Remote Sensing Centre (2010). *Wastelands Atlas of India 2010*. Department of Land
867 Resources, Ministry of Rural Development, Delhi

868 Nowell, K. and Jackson, P. eds., (1996). *Wild cats: status survey and conservation action plan*
869 (Vol. 382). Gland: IUCN.

870 Richards, D. R., & Friess, D. A. (2016). Rates and drivers of mangrove deforestation in Southeast
871 Asia, 2000–2012. *Proceedings of the National Academy of Sciences*, 113(2), 344-349.

872 Shekhar Palei, H., Pratap Das, U. and Debata, S., (2018). The vulnerable fishing cat *Prionailurus*
873 *viverrinus* in Odisha, eastern India: status and conservation implications. *Zoology and Ecology*,
874 28(2), pp.69-74.

875 Qasim, H., Luqman, M., & Khan, S. (2016). A study of forest land cover changes using satellite
876 remote sensing in Thatta District Pakistan. *Science International*, 28(3).

877 Rahman, A. U., & Shaw, R. (2017). Fragile Mangroves and Increasing Susceptibility to Coastal
878 Hazards in Pakistan. In *Participatory Mangrove Management in a Changing Climate* (pp. 17-30).
879 Springer, Tokyo.

880 Rainey, H. J., & Kong, K. (2010). A fishing cat observation from northern Cambodia. *Cat News*,
881 52, 8-9.

882 van Rees, C.B., Waylen, K.A., Schmidt-Kloiber, A., Thackeray, S.J., Kalinkat, G., Martens, K.,
883 Domisch, S., Lillebø, A.I., Hermoso, V., Grossart, H.P. & Schinegger, R., (2021). Safeguarding
884 freshwater life beyond 2020: Recommendations for the new global biodiversity framework from
885 the European experience. *Conservation Letters*, 14(1), p.e12771.

886 Revenga C. & Kura, Y. (2003). Status and trends of biodiversity of inland water ecosystems .
887 Montreal (Canada) Secretary of the Convention on Biological Diversity technical series no.11

888 Roberts, T.J., (1977). The Mammals of Pakistan. Ernest Benn Limited. London and Tonbridge,
889 151-153.

890 Rodewald, A. D., Strimas-Mackey, M., Schuster, R., & Arcese, P. (2019). Tradeoffs in the value
891 of biodiversity feature and cost data in conservation prioritization. *Scientific reports*, 9(1), 1-8.

892 Sadhu, A., and GV Reddy. (2013). First Evidence of Fishing Cat in the Ranthambore Tiger
893 Reserve, Rajasthan, India. *Cat News* 58: 36-37.

894 Safi K, Armour-Marshall K, Baillie JEM, Isaac NJB. (2013). Global Patterns of Evolutionary
895 Distinct and Globally Endangered Amphibians and Mammals. PLoS ONE 8:4–12.

896 Sanderson, J. G. (2009). How the fishing cat came to occur in Sumatra. *Cat News*, 50, 6-9.

897 Santini, L., Butchart, S.H.M., Rondinini, C., Benítez-Lopez, A., Hilbers, J.P., Schipper, A.M.,
898 Cengic, M., Tobias, J.A., Huijbregts, M.A.J., (2019). Applying habitat and population-density
899 models to land-cover time series to inform IUCN Red List assessments. *Conserv. Biol.*
900 <https://doi.org/10.1111/cobi.13279>. John Wiley & Sons, Ltd (10.1111). Available from.

901 Schmitt, S., Pouteau, R., Justeau, D., De Boissieu, F., & Birnbaum, P. (2017). ssdm: An r package
902 to predict distribution of species richness and composition based on stacked species distribution
903 models. *Methods in Ecology and Evolution*, 8(12), 1795-1803.

904 Subedi N., Thapa G. J., Yadav H., Jhala Y. V., Qureshi Q., Vattakaven J. & Borah J. (2014). Tigers
905 of the Transboundary Terai Arc Landscape: Status, distribution and movement in the Terai of India
906 and Nepal. National Tiger Conservation Authority, Government of India, and Department of
907 National Park and Wildlife Conservation, Government of Nepal

908 Shah, V. B., & McRae, B. H. (2008, August). Circuitscape: a tool for landscape ecology. In
909 *Proceedings of the 7th Python in Science Conference* (Vol. 7, pp. 62-66). Pasadena, CA: SciPy.

910 Shrestha, M., Piman, T., & Grünbühel, C. (2021). Prioritizing key biodiversity areas for
911 conservation based on threats and ecosystem services using participatory and GIS-based modeling
912 in Chindwin River Basin, Myanmar. *Ecosystem Services*, 48, 101244.

913 Silva, A.P., Mukherjee, S., Ramakrishnan, U., Fernandes, C. and Björklund, M., (2020). Closely
914 related species show species-specific environmental responses and different spatial conservation
915 needs: Prionailurus cats in the Indian subcontinent. *Scientific reports*, 10(1), pp.1-12.

916 De Simone, W., Allegranza, M., Frattaroli, A. R., Montecchiari, S., Tesei, G., Zuccarello, V., &
917 Di Musciano, M. (2021). From Remote Sensing to Species Distribution Modelling: An Integrated
918 Workflow to Monitor Spreading Species in Key Grassland Habitats. *Remote Sensing*, 13(10),
919 1904.

920 Song, X. P., Hansen, M. C., Stehman, S. V., Potapov, P. V., Tyukavina, A., Vermote, E. F., &
921 Townshend, J. R. (2018). Global land change from 1982 to 2016. *Nature*, 560(7720), 639-643.

922 Strayer DL & Dudgeon D. (2010). Freshwater biodiversity conservation: Recent progress and
923 future challenges. *Journal of the North American Benthological Society* 29: 344–358.

924

925 Sultan S. E. & Spencer H. G. (2002). Metapopulation structure favors plasticity over local
926 adaptation. *American Naturalist* 160:271–283.

927 Sunquist, M. & Sunquist, F. (2014). *Wild Cats of the World*. University of Chicago Press.

928 Talegaonkar, R. K., Momin, A. C., Nigam, P., & Pathak, M. (2018). Record of Fishing Cat from
929 Bandhavgarh Tiger Reserve, Madhya Pradesh, India. *Cat News*, 68, 5-6.

930 Taylor, I. R., Baral, H. S., Pandey, P., & Kaspal, P. (2016). The conservation status of the Fishing
931 Cat *Prionailurus viverrinus* Bennett, 1833 (Carnivora: Felidae) in Koshi Tappu Wildlife Reserve,
932 Nepal. *Journal of Threatened Taxa*, 8(1), 8323-8332.

933 Tensen, L. (2018). Biases in wildlife and conservation research, using felids and canids as a case
934 study. *Global Ecology and Conservation*, 15, e00423.

935 Thanh Noi, P., & Kappas, M. (2018). Comparison of random forest, k-nearest neighbor, and
936 support vector machine classifiers for land cover classification using Sentinel-2 imagery. *Sensors*,
937 18(1), 18.

938 Thaung, R., Muñoz, V.H., Holden, J., Willcox, D. and Souter, N.J., (2018). The Vulnerable fishing
939 cat *Prionailurus viverrinus* and other globally threatened species in Cambodia's coastal mangroves.
940 *Oryx*, 52(4), pp.636-640.

941 Thudugala, A. (2015). Fishing Cat conservation in hill country, Sri Lanka. In: A. Appel and J. W.
942 Duckworth (eds.), Proceedings of the First International Fishing Cat Symposium, 25-29, Nov,
943 2015, Nepal. FCWG, UK.

944 Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J.,
945 Dalton, J., Darwall, W., Edwards, G. & Harrison, I., (2020). Bending the curve of global freshwater
946 biodiversity loss: an emergency recovery plan. *BioScience*, 70(4), pp.330-342.

947 Tittensor, D. P., Walpole, M., Hill, S. L. L., Boyce, D. G., Britten, G. L., Burgess, N. D., ... Ye,
948 Y. (2014). A mid-term analysis of progress toward international biodiversity targets. *Science*, 346,
949 241– 244.

950 Ratnayaka, A. A. W. (2021). First pictures of fishing cats in the hyper urban landscape of Colombo,
951 Sri Lanka. *Cat News* 73(Spring), 19-20.

952 Ratnayaka, A. A., Serieys, L. E., Prasad, T., Leighton, G. R., Sanderson, J. G., & Leung, L. K. P.
953 (2021). Urban habitat use and home ranges of fishing cats in Colombo, Sri Lanka. *Mammalian*
954 *Biology*, 1-7.

955 Veettil, B. K., Pereira, S. F. R., & Quang, N. X. (2018). Rapidly diminishing mangrove forests in
956 Myanmar (Burma): a review. *Hydrobiologia*, 822(1), 19-35.

957 Veron, G., Patterson, B. D., & Reeves, R. (2007). Global diversity of mammals (Mammalia) in
958 freshwater. In *Freshwater Animal Diversity Assessment* (pp. 607-617). Springer, Dordrecht.

959 Villero, D., Pla, M., Camps, D., Ruiz-Olmo, J., & Brotons, L. (2017). Integrating species
960 distribution modelling into decision-making to inform conservation actions. *Biodiversity and*
961 *Conservation*, 26(2), 251-271.

962 Webb, E. L., Jachowski, N. R., Phelps, J., Friess, D. A., Than, M. M., & Ziegler, A. D. (2014).
963 Deforestation in the Ayeyarwady Delta and the conservation implications of an internationally-
964 engaged Myanmar. *Global Environmental Change*, 24, 321-333.

965 Wickham, H. (2011). ggplot2. *Wiley Interdisciplinary Reviews: Computational Statistics*, 3(2),
966 180-185.

967 Wilkinson C., Sudara S. & Chou L. M. (1994) Proceedings of the Third Aseanaustralia Symposium
968 on Living Coastal Resources. Australian Institute of Marine Science, Townsville

969 Willcox, D. H. A. (2015). Fishing Cat status in Vietnam. In: A. Appel and J. W. Duckworth (eds.),
970 Proceedings of the First International Fishing Cat Symposium, 25-29, Nov, 2015, Nepal. FCWG,
971 UK.

972 World Wildlife Fund [WWF]. (2020). In: R.E.A. Almond, M. Grooten, T. Petersen (Eds.) Living
973 planet report 2020 – Bending the curve of biodiversity loss. Gland, Switzerland: WWF.

974 World Wildlife Fund [WWF]. (2021). In: The World’s Forgotten Fishes. Gland, Switzerland:
975 WWF.

976 Wyborn, C. and Evans, M.C., (2021). Conservation needs to break free from global priority
977 mapping. *Nature Ecology & Evolution*, 5(10), pp.1322-1324.

978 Xiao, S., Wu, W., Guo, J., Ou, M., Pueppke, S. G., Ou, W., & Tao, Y. (2020). An evaluation
979 framework for designing ecological security patterns and prioritizing ecological corridors:
980 application in Jiangsu Province, China. *Landscape Ecology*, 35(11), 2517-2534.

981 Xu, T., Weng, B., Yan, D., Wang, K., Li, X., Bi, W., ... & Liu, Y. (2019). Wetlands of International
982 Importance: Status, Threats, and Future Protection. *International Journal of Environmental*
983 *Research and Public Health*, 16(10), 1818.

984 Yu, H., Wang, Y., Eme, C., Fan, X., Rong, Y., Zhang, Q., & Liang, Z. (2021). Construction of
985 Ecological Network Based on Multi-Scale Conversion and Nesting. *Water*, 13(9), 1278.

986 Zanin, M., & dos Santos Neves, B. (2019). Current felid (Carnivora: Felidae) distribution, spatial
987 bias, and occurrence predictability: testing the reliability of a global dataset for macroecological
988 studies. *Acta Oecologica*, 101, 103488.

LIST OF TABLES

	AUC	Kappa	Threshold	Presence (Area in km ²)	Absence (Area in km ²)
EcoT₁	0.821	0.642	0.521	1106360	8646851
EcoT₂	0.834	0.668	0.551	948753.2	8804458
UrbT₁	0.847	0.694	0.628	781283.3	8971928
UrbT₂	0.827	0.654	0.535	745619.1	9007592

Table 1: AUC values of all models along with threshold

	EcoT ₁ to EcoT ₂	UrbT ₁ to UrbT ₂
Habitat gain	46014.0267	151373.806
Habitat loss	203621.1354	185824.7738
Percent gain (%)	4.159	19.375
Percent loss (%)	18.404	23.784

Table 2: Changes in area of suitable habitat for FC in the two scenarios and time intervals.
Note: Area in km². EcoT₁ - Ecological scenario for T₁; EcoT₂ - Ecological scenario for T₂;
UrbT₁ - Urban scenario for T₁; UrbT₂ - Urban scenario for T₂.

River Basins	Location	Highest Priority	High Priority	Moderate Priority	Total no of LCUs
Fishing Cat connectivity scenario					
Indus Basin	South Asia	8	5	1	14
GBB	South Asia	15	10	10	35
Mahanadi basin	South Asia	1	-	-	1
Godavari-Krishna delta	South Asia	-	-	1	1
Ayeyarwady basin	South-east Asia	-	-	1	1
Salween delta	South-east Asia	-	-	1	1
Chao Phraya river system	South-east Asia	-	-	2	2
Mekong Basin	South-east Asia	-	-	2	2
Red River Delta	South-east Asia	-	-	-	0
Least urbanized unit scenario					
Indus Basin	South Asia	9	3	1	13
GBB	South Asia	6	7	4	17
Mahanadi basin	South Asia	-	-	-	0
Godavari-Krishna delta	South Asia	-	-	1	1
Ayeyarwady basin	South-east Asia	-	-	1	1
Salween delta	South-east Asia	-	-	-	0

Chao Phraya river system	South-east Asia	-	-	2	2
Mekong basin	South-east Asia	3	2	1	6
Red River Delta	South-east Asia	1	-	1	2

Table 4: Different LCUs selected in river basins of South and South-east Asia

LIST OF FIGURES

Fig 1: Variable Importance Scores for the ecological scenario

Fig 2: Variable Importance Scores for the urban scenario

Bio 1 = Annual Mean Temperature

Bio 14 = Precipitation of Driest Month

Bio 18 = Precipitation of Warmest Quarter

Bio 10 = Mean Temperature of Warmest Quarter

CIFOR = global wetland maps

LST_Feb = Land Surface Temperature in February

LST_Sept = Land Surface Temperature in September

NDVI_Feb = Normalized Difference Vegetation Index for February

NDVI_Sept = Normalized Difference Vegetation Index for September

SRTM = global elevation data

Fig 3: Predicted global distribution of Fishing Cat along river basins of South and Sout-east Asia with probabilities of occurrence

Fig 4: Ecoregions with Fishing Cat predicted to have more than 80% probability of occurrence. Note: Symbology inflated for better visualization.

Fig 5: Change in the predicted distribution of Fishing Cat from 2010 to 2020, in an ecological change only scenario.

Fig 6: Change in predicted global distribution of Fishing Cat due to urbanisation between T1 and T2

Fig 7: Least Cost Corridors (LCCs) and Line Densities of LCCs for global Fishing Cat connectivity. Note: Higher cost values in LCC denote higher friction in movement, while higher line density values denote most traveled LCCs.

Fig 8: Least Cost Path (LCP) with varying levels of resistance to global Fishing Cat connectivity.

Fig 9: Circuitscape generated corridor showing higher current flow intensity in most suitable movement corridors (above). Corridors with a minimum width (4.6 km) and a high density of corridor path depict the pinch-points, i.e., bottlenecks in the corridor (below).

Fig 10: Landscape Conservation Units according to the least urbanized scenario (above) and most suitable habitat units that facilitate connectivity (below).

Appendix Data Sources

Habitat Variables	Spatial Resolution	Citation
Variables used in the Ecological Scenario		
Worldclim v.2.0 bioclimatic layers (n=19)	2.5 minute (~4.6 km)	Fick, S.E. and R.J. Hijmans, 2017. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. <i>International Journal of Climatology</i> 37 (12): 4302-4315.
Monthly mean of Normalised Difference Vegetation Index (NDVI) layers extracted from the 16-Day L3 Global 1 km – MOD13A2v006. Two NDVI layers from the same month were used for calculating the monthly means (n=12).	1 km raster layers resampled to 2.5 minute (~4.6 km)	Didan, K. (2015). MOD13A2 MODIS/Terra Vegetation Indices 16-Day L3 Global 1km SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-02-20 from https://doi.org/10.5067/MODIS/MOD13A2.006
Elevation derived from SRTM GL3v003	90 m resampled to 2.5 minute (~4.6 km)	NASA JPL (2013). NASA Shuttle Radar Topography Mission Global 3 arc second [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-07-15 from https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL3.003
Terrestrial ecoregions of the World, The Nature Conservancy classification	Vector data, rasterised at 2.5 minute spatial resolution	Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'Amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., Kassem, K. R. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. <i>Bioscience</i> 51(11):933-938.
Terrestrial ecoregions of the World, Worldwide Fund for Nature classification	Vector data, rasterised at 2.5 minute spatial resolution	Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'Amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., Kassem, K. R. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. <i>Bioscience</i> 51(11):933-938.

Global Wetlands v3	236 m resampled to 2.5 minute (~4.6 km)	Gumbrecht, T.; Román-Cuesta, R.M.; Verchot, L.V.; Herold, M.; Wittmann, F; Householder, E.; Herold, N.; Murdiyarso, D., 2017, "Tropical and Subtropical Wetlands Distribution version 2", https://doi.org/10.17528/CIFOR/DATA.00058 , Center for International Forestry Research (CIFOR), V3, UNF:6:Bc9aFtBpam27aFOCMgW71Q== [fileUNF]
Digital Soil Map of the World	Vector data, rasterised at 2.5 minute spatial resolution	Land and Water Development Division, FAO, Rome
Euclidean Distance from water layer developed using – using the World Water Bodies data released by ESRI Data & Maps	Raster layer created in ArcGIS with 2.5 minute spatial resolution	ESRI Data & Maps, 2015
Additional variables for the Urban Impact Scenario		
Monthly Land Surface Temperature and Emissivity (LST&E) extracted from MOD11C3 Version 6 (n=12)	0.05 degree (~5.6 km) resampled to 2.5 minute (~4.6 km)	Wan, Z., Hook, S., Hulley, G. (2015). MOD11C3 MODIS/Terra Land Surface Temperature/Emissivity Monthly L3 Global 0.05Deg CMG V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-07-16 from https://doi.org/10.5067/MODIS/MOD11C3.006
VIIRS Day/Night Band Nighttime Lights Version 1 Tiles with the ranges 00N60E and 75N0E for all the months of 2013 (T1) and 2019 (T2) were downloaded, resampled, rescaled and an annual mean was calculated.	15 second (~450 m) resampled to 2.5 minute (~4.6 km)	C. D. Elvidge, K. Baugh, M. Zhizhin, F. C. Hsu, and T. Ghosh, “VIIRS night-time lights,” International Journal of Remote Sensing, vol. 38, pp. 5860–5879, 2017.

Supplementary Information

River basins	Countries	Wetland complexes	Provinces/ States/ Districts
Indus basin			
A. Lower Indus Basin	A i) Pakistan	i) Wetland complexes (Haleji lake, Keenjhar lake, Chotiari reserve, Nara canal area, Qualandri creek in the Indus delta, Ketu Bundar mangroves, the Karachi harbour area, Jubho lagoon and Nurri lagoon)	i) Sindh Province
		ii) Areas around the Hub dam adjacent to Sindh province and Miani Hor mangroves	ii) Balochistan Province
B. Middle Indus Basin	B i) Pakistan	i) Waterlogged and swampy areas formed by seepage from unlined canals	i) Punjab Province
Ganges Brahmaputra Basin (GBB)			
A. Wetlands of the Terai region	A i) India	i) swamps, marshes and seasonally inundated grasslands in National Parks (Jim Corbett, Dudhwa, Katarniaghat, Kishanpur and Valmiki Tiger Reserve)	i) State of Uttar Pradesh
	ii) Nepal	ii) mudflats, reeds beds, freshwater marshes of Koshi Tappu Wildlife Reserve, Jagdishpur Ramsar site, Chitwan National Park, Parsa	ii) Districts of Sunsari, Saptari, Udayapur, Kapilvastu, Kailali

B. Wetlands of Gangetic Plains	B i) India	National Park, Ghodaghodi Tal Ramsar site i) shallow wetlands, riverine wetlands and floodplains of Yamuna and Ganga including Okhla Bird Sanctuary, Baghel Tal, Bakhira Lake, Surha Tal, Dahar Lake, Soor Sarovar Bird Sanctuary, Samaspur Lake ; Ramsar site with wetland stretch between Brijghat and Narora; shallow wetlands in Bihar like Kanwar Jheel, Kusheshwarsthan, Bariella, Vikramshila Dolphin Sanctuary, Moti Jheel and various wetland complexes in several districts of West Bengal.	i) States of Delhi, Agra, Uttar Pradesh, Bihar, West Bengal (including districts of Nadia, Murshidabad, Bardhaman, Howrah, Hooghly, East and West Midnapore)
C. Wetlands within the valley of Brahmaputra, its tributaries and distributar-ies	C i) India	i) tall grassland wetland habitat, oxbow lakes and riverine wetlands including Deepor Beel Ramsar Site, Majauli island, Dhir-Dilpai-Dakra complex, Tamranga-Dalani complex, Urpod Beel, Chandubi Lake, Orang, Laokhowa, Kaziranga National Park, Jaldapara Wildlife Sanctuary and Gajoldoba wetland	i) State of Assam and West Bengal
D. Wetlands of Gangetic Delta	ii) Bangladesh	ii) seasonally flooded marshy wetlands and swamp forests of Haor basin of Sylhet and eastern Mymensingha, Tanguar Haor Ramsar Site, Hakaluki Haor	ii) Districts of Sylhet, Mymensingh, Sunamganj, Moulvibazar
	D i) India	i) seasonally flooded wetlands, depressed lands,	i) State of West Bengal

	ii) Bangladesh	river creeks, mangrove swamps and marshes including the East Kolkata Wetlands Ramsar Site; Sunderbans delta ii) deltaic wetlands including Marijat Haor, Atadanga Haor, Chanda-Bahgia Beel, Sowagram-Gopalpur Beel, Dakatia Beel, Naldanga Beel, Tarail Beel; Sunderbans delta	ii) Districts spanning most of Bangladesh, except for its hilly tracts
Mahanadi basin	i) India	i) depressions, floodplain wetlands and ephemeral wetlands including marshes and mangroves connected to Mahanadi, Brahmani and Baitarani rivers; Debi mouth; Bhitarkanika Ramsar site; Chilika lagoon	i) Districts of Kendrapada, Puri, Khordha; Ganjam
Godavari-Krishna delta	i) India	i) mangrove swamps, inland and coastal wetlands	i) Districts of Guntur, Krishna, East Godavari, West Godavari, Visakhapatnam, Vizianagaram, Srikakulam
A. Ayeyarwady basin B. Salween delta	i) Myanmar i) Myanmar	i) coastal mangroves and freshwater swamp forests i) floodplain wetlands and mangrove forests	i) States of Ayeyarwady, Bago, Rakhine, Yangon, Kachin, Sagaing i) States of Kayin and Mon
Chao Phraya river system	i) Thailand	i) riverine wetlands along the Mun, Chi and Songkhram like the Kut Ting Marshland, a Ramsar site; inland and coastal wetlands including Non Thung Thong wetland drained by Tapi river; Bung Khong Long Ramsar Site; Thale sap	i) Provinces of Nongkhai province, Nakohn si Thammarat, Pattani, Narathiwat, Surat Thani, Patthalung, Songkhla, Phang

		estuary, Laem Kham marshes; Nong Plak Phraya wetlands, Krabi estuary	Nga, Phuket, Trang, Satun
Lower Mekong Basin	i) Cambodia ii) Vietnam	i) flooded forests, swamps, marshes and grasslands including Stung Treng Ramsar site, Tonle Sap Ramsar Site, Boeing Chhmar Ramsar Site, Bassac marshes Ramsar Site ii) Tram Chim National Park or Plain of Reeds Ramsar Site, Lang Sen Wetland Reserve, U Minh wetland complex	i) Provinces of Stung Treng, Battambang, Kampong Thom, Kandal ii) Provinces of Dong Thap, Long An, Kien Giang, Ca Mau
Red River Delta	i) Vietnam	i) mangroves and intertidal habitats of Red River Delta Biosphere Reserve	i) Districts of Xuan Thuy and Tien Hai

S1: Mainland river basins along with transboundary freshwater units, wetland complexes and jurisdictional boundaries with predicted occurrence of Fishing Cat

Key Areas	Topographic zones (Coastal: 0-100m / Intermediate Plains: 100-500m / Central Highlands: >500m)	Wetland complexes	Provinces / States / Districts
Salt water wetlands (Estuaries)	Coastal plains	Estuaries around Sri Lanka including Kala Oya Estuary	Western Provinces
Salt water wetlands (Lagoons)	Coastal plains	Lagoons are found around the coast of Sri Lanka including the Chundikulam and Negambo Lagoons	Northern and North-western Provinces
Salt water wetlands (Mangroves)	Coastal plains	Kala Oya Estuary, southern boundary of the Wilpattu National Park, mangroves associated with Negombo and Chilaw Lagoons	Northern, North-western, Western Provinces

Inland freshwater wetlands (Rivers, streams)	Coastal plains and intermediate plains	Rivers and streams associated habitats	Eastern Province
Inland freshwater wetlands (Swamp forest and villus)	Intermediate plains	Flood Plains National Park, Somawathiya	North- central and Western Provinces
Man-made wetlands (Tanks, reservoirs, and rice paddy fields)	Intermediate Plains	Man-made tanks and paddy fields simulating Fishing Cat habitat	North-central and Western, Provinces
Protected landscapes (national parks, sanctuaries, and protected areas through government sectors)	Coastal plains and Intermediate plains	Protected areas by Department of Wildlife Conservation, Forest Department, or other government bodies like Municipal Councils)	Wilpattu National Park,

S2: Key areas in Sri Lanka in wetland complexes with jurisdictional boundaries with predicted occurrence of Fishing Cat